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INDUSTRIAL WASTE GUIDE ON THERMAL POLLUTION

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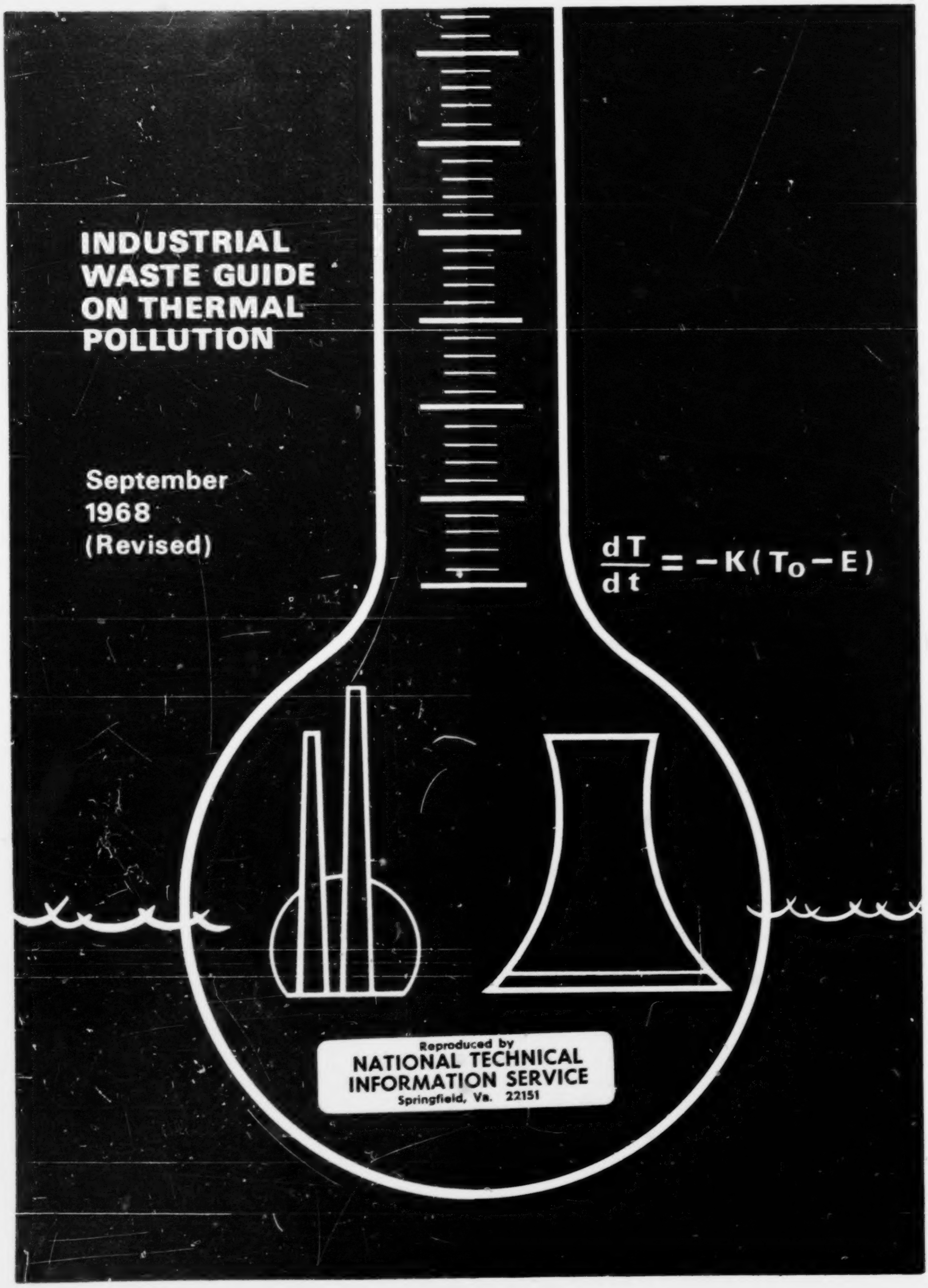

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A guide to the sources, effects, and methods of control of thermal water pollution is presented to aid state, federal, and local regulatory personnel, community and regional planners, and industrialists in making sound decisions on handling hot discharges. A guide to more specific literature is included with a general description of the subject for the user's basic orientation. The general topics covered are heat loads from general industry, electric power, and manufacturing; physical, chemical, and biological effects; and methods of control and utilization of excess heat. A bibliography of 91 references is included. (Knapp-USGS)

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INDUSTRIAL WASTE GUIDE
ON
THERMAL POLLUTION

Revised

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Federal Water Pollution Control Administration
Northwest Region
Pacific Northwest Water Laboratory
Corvallis, Oregon
September 1968

FOREWORD

Industry's accelerating emission of heated wastes to the environment poses hazards that have triggered an acute awareness and concern on the part of the public, the policy makers and industry itself. Establishment of State-Federal water quality standards brings the concern into sharp focus. The waters of the nation cannot accept heated wastewaters without quality degradation and human sacrifice of beneficial uses. Adding to the problem is the increasing lead time required for delivery of heavy power generating equipment and other industrial machinery, causing hurried management and public policy decisions on plant siting, design and equipment that will have long-range impact on the environment.

This Industrial Waste Guide on Thermal Pollution seeks to assist State, Federal and local regulatory personnel, community and regional planners and industrialists in making sound decisions. The literature contains much information on thermal pollution. Yet, the operating engineer is hard pressed for the time required to search the widespread reference material in sufficient depth to obtain a working understanding of the subject. This Guide provides such orientation and directs the investigator to sources of more detailed information.

The principal authors, Alden G. Christianson and Bruce A. Tichenor, have drawn material from many sources as well as on their own experiences for this document. Nevertheless, the Guide is less than totally adequate. Deficiencies are recognized in today's knowledge of heat sources and effects and of technology for water temperature prediction and control. Even as this treatise is published, a revision is underway to include new facts and knowledge emitting from governmental and privately sponsored research.

We wish to express appreciation to our numerous colleagues in State pollution control agencies who cooperated in developing the content of the Guide. Such cooperation foretells a vigorous nationwide attack on thermal pollution of our water resources.

Frank H Rainwater
Frank H. Rainwater, Chief
National Thermal Pollution Research Program
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GENERAL PROBLEM

Waste heat is a pollutant equally as dangerous to our waters as the more tangible forms of wastes which enter our nation's rivers, lakes, and estuaries. Thermal pollution has been defined as man-caused deleterious changes in the normal temperature of water (75).

Human activity can change the normal temperature of water in many ways. Temperature changes may be induced by altering the environment of a watercourse, e.g., through road building or logging, by creating impoundments, or by diverting flows for irrigation. Or, water temperatures may be changed directly by adding or taking away heat.

Present and future demands indicate that industrial cooling water, when viewed on the national scale, is a first-order source of waste heat. The electric power generating industry alone accounts for about 80% of the cooling water used. Therefore, the best single index of the thermal pollution potential lies in projecting future electric power production (75). Power generation has approximately doubled each 10 years during this century, and estimated future demands indicate a shortening of the time span for similar increases (60,74). Waste heat output has not multiplied as fast as power generation because of continued improvements in thermal plant efficiency and development of hydropower. However, fossil-fueled plants are reaching a limit of efficiency because of metallurgical restrictions, and nuclear plants, planned or built, necessarily waste an even higher proportion of heat than fossil-fueled plants. Waste heat increase can be expected to more closely parallel power production increase in the foreseeable future.

With these considerations in mind, heat rejection from the predicted mixture of nuclear and fossil power plants is expected to increase almost ninefold by the year 2000 (44,60). Waste heat output from the manufacturing industries will also increase. However, the demand for electricity is expected to continue to increase at a more pronounced rate than the demand for manufactured goods (75). This indicates a somewhat smaller rate of increase in heat rejection from manufacturing as compared with the power industry.

The problem is one of managing tremendous amounts of waste heat in a manner that will maintain, or enhance if necessary, the physical, chemical, and biological nature of our water resources. Water quality standards are being implemented to protect these resources, but thermal pollution control measures are costly and complicated. An estimate by the Federal Water Pollution Control Administration (FWPCA) places the cost of cooling facilities needed over the five years 1968 through 1972 at $1.8 billion (74). By comparison, in one year alone (1965), $3 billion was spent on sport fishing (3). Thus, the potential effect of thermal pollution on this and other beneficial water uses must be considered. We must develop a thorough understanding of the causes, effects, and control of thermal pollution in order to apply equitable, reasonable, and effective approaches toward its solution.

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INDUSTRIAL WASTE-HEAT LOADS

GENERAL

Tremendous amounts of water are used specifically for cooling purposes. Almost one-half of all water used in the United States is utilized for cooling and condensing by the power and manufacturing industries (74). In 1964 this amounted to about 50 trillion gallons, nearly 90% of the intake water for these industries (79). Cooling water usage by industry is cited in Table 1.

TABLE 1 (73)

USE OF COOLING WATER BY U.S. INDUSTRY, 1964

Industry	Cooling Water Intake (Billions of Gallons)	% of Total
Electric Power..................	40,680	81.3
Primary Metals..................	3,387	6.8
Chemical and Allied Products....	3,120	6.2
Petroleum and Coal Products.....	1,212	2.4
Paper and Allied Products.......	607	1.2
Food and Kindred Products.......	392	0.8
Machinery.......................	164	0.3
Rubber and Plastics.............	128	0.3
Transportation Equipment........	102	0.2
All Other.......................	273	0.5
TOTAL	50,065	100.0

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ELECTRIC POWER INDUSTRY

Power Requirements and Sources

Power production has steadily increased throughout our nation's history. Table 2 indicates the amounts of electrical power used in certain past years as well as projected national requirements through 1985.

TABLE 2 (4)

U.S. ELECTRIC POWER -- PAST USE, FUTURE REQUIREMENTS

Year	Billion KWH
1912	11.6
1960	753
1965	1,060
1970	1,503
1975	2,022
1980	2,754
1985	3,639

For almost a half-century power generation has increased at a rate of 7.2% annually, virtually doubling every 10 years (74). This trend is expected to continue, and possibly accelerate, in future years (60).

Power is usually generated by hydro- or steam-electric plants, with the latter process requiring cooling water for waste heat removal. The remaining sites which are suitable for hydroelectric stations are limited, so the power industry must depend more and more on thermal power generation to meet future needs. As shown in Table 2, total power consumption in 1960 was over 65 times that for 1912. During this same period, power production from fossil-fueled, steam-electric plants multiplied by a factor of 85-plus (47). At the present time thermal plants produce approximately 81% of the electricity generated in the United States; predictions indicate this figure may reach 92% by the year 2000, when two-thirds of the plants may operate on nuclear fuel (44,60). Thus, thermal plants will continue to gain a larger portion of a steadily increasing market for power. Waste heat production will increase proportionately, which in turn reflects the increase in waste heat disposal that we must accomodate.

Plant Evaluation

The overall thermal efficiency (η_t) of a steam-electric plant is calculated as:

$$\eta_{t(\%)} = \frac{\text{Electrical Output}}{\text{Thermal Input}} \times 100$$

For one kilowatt-hour:

$$\eta_{t(\%)} = \frac{\text{3413 BTU/KWH}}{\text{3413 BTU/KWH + Waste Heat (BTU/KWH)}} \times 100$$

The denominator of the efficiency equation above represents the "heat rate" of a plant, which is defined as the average amount of heat required to produce one kilowatt-hour of electricity. This measure is used throughout the power industry for comparisons. It is actually a measure of thermal efficiency due to the inverse proportionality of the two.

Thermal plant heat rates on a national average basis have decreased continually as more efficient power production techniques were employed (See Table 3).

TABLE 3 (30)

STEAM-ELECTRIC PLANT STATISTICS--NATIONAL AVERAGE BASIS

Year	Heat Rate (BTU/KWH)	Thermal Efficiency (%)	Waste Heat To Cooling Water (BTU/KWH)
1930	19,800	17.24	13,420
1940	16,400	20.81	10,530
1950	14,030	24.33	8,510
1960	10,760	31.72	5,730
1962	10,558	32.33	5,560
1964	10,462	32.62	5,480
1966	10,415	32.77	5,440

Sizable gains in efficiency, however, are a thing of the past. The most efficient fossil-fueled plant presently operates at about 40% efficiency. This figure is generally assumed to be a ceiling which the national average for fossil-fueled plants may ultimately approach (74). Efficiency of nuclear plants of the pressurized or boiling water reactor types now being built or planned to 1975 will not exceed about 33% (72,74).

Table 3 includes estimates of the amounts of heat wasted to cooling water in BTU's per kilowatt-hour of electricity produced.

These values are less than those representing the "Waste Heat" portion of the efficiency equation because of in-plant and stack losses. Plant design and operating data indicate that 15% of the thermal input is a reasonable approximation of these losses for coal-fired plants; for calculations on a kilowatt-hour basis this equals 15% of the plant heat rate. Therefore, the following equation applies to fossil-fueled plants:

$$\text{Heat to cooling water (BTU/KWH)} = 0.85 \times \text{Heat Rate} - 3413$$

The amount of heat rejected to cooling water from nuclear plants may be computed in the same manner, except that heat losses up a stack are not involved. Typical in-plant losses are about 5% of the heat rate, so that the resulting equation which applies to nuclear-fueled plants is:

$$\text{Heat to cooling water (BTU/KWH)} = 0.95 \times \text{Heat Rate} - 3413$$

As an example of the quantities of waste heat which can be expected in the future, the two types of plants are compared. For a fossil-fueled plant at 40% efficiency:

$$\text{Heat Rate} = \frac{3413}{n_t \div 100} = \frac{3413}{.40} = 8533 \text{ BTU/KWH}$$

$$\text{Heat to cooling water} = 0.85(8533) - 3413 = 3800 \text{ BTU/KWH}$$

For a nuclear-fueled plant at 33% efficiency:

$$\text{Heat Rate} = \frac{3413}{.33} = 10{,}342 \text{ BTU/KWH}$$

$$\text{Heat to cooling water} = 0.95(10{,}342) - 3413 = 6400 \text{ BTU/KWH}$$

We may infer from these calculations that the advent of nuclear power plants will not lessen, but rather will increase, by over 60% (32), the amount of heat rejected to cooling water per KWH of electricity they produce. This factor is taken into account in the estimated ninefold increase in heat rejection by the year 2000 as previously mentioned.

A final observation is noteworthy in regard to waste heat rejection: on a percentage basis, the incremental decrease in waste heat to cooling water per KWH is much greater than the increase in efficiency which is responsible. For example, Table 3 indicates that efficiency increased by about 15.5% from 1930 to 1966; the amount of waste heat to cooling water decreased almost 60% in the same period. Hence, any gain in efficiency is multiplied in terms of decreased waste heat rejection.

MANUFACTURING INDUSTRIES

As indicated in Table 1, about 80% of all industrial cooling water is used by the power industry, and the remaining 20% by manufacturing industries. Manufacturers' cooling facility needs are expected to increase at a 4.5% annual rate, compared to the 7.2% annual increase expected by the power industry (74).

To assess the impact of an industry or an industrial complex on the thermal properties of a stream, one must determine the quantity of waste heat, i.e., total BTU's, discharged from each plant.

Specific values of heat wasted by various processes are generally not applicable to individual plants, due to the wide range of production processes, equipment combinations, and efficiencies employed. Therefore, no attempt to formulate quantitative guidelines will be made here. Rather, it is suggested that the situation be approached through studying each manufacturing plant's discharge. In this manner, incorrect assumptions will not be used and a more valid heat load determination will be assured.

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EFFECTS

PHYSICAL

Temperature affects many physical properties of water. Of these, the most significant to water quality are density, viscosity, vapor pressure and solubility of dissolved gases. Table 4 shows the effect of incremental changes in temperature on these properties for fresh water.

TABLE 4

WATER PROPERTIES

Temperature		Density	Abs. Viscosity	Pressure	Dissolved Oxygen Saturation
(°C)	(°F)	(gm/cm^3)	(centipoises)	(mm Hg)	(mg/l)
0	32	0.99987	1.7921	4.58	14.6
4	39.2	1.00000			
5	41	0.99999	1.5188	6.54	12.8
10	50	0.99973	1.3077	9.21	11.3
15	59	0.99913	1.1404	12.8	10.2
20	68	0.99823	1.0050	17.5	9.2
25	77	0.99707	0.8937	23.8	8.4
30	86	0.99567	0.8007	31.8	7.6
35	95	0.99406	0.7225	42.2	7.1
40	104	0.99224	0.6560	55.3	6.6

Stokes' law describes the velocity of settling particles in a non-turbulent medium according to the following equation.

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$$V = \frac{d^2g}{18\mu}(\rho_s - \rho_w)$$

where V = settling velocity, cm/sec
ρ_s = density of settling particle, gm/cm^3
ρ_w = density of water, gm/cm^3
μ = viscosity of liquid, poises
d = diameter of particle, cm
g = acceleration of gravity = 980 cm/sec^2

As indicated, settling velocity is inversely proportional to the water viscosity and density. Thus, both properties contribute to increased settling rates at elevated temperatures. These increased settling rates may promote better water treatment plant operation, though probably to no measurable degree. A difference in settling velocities can have a significant effect on the location and amount of sediment and sludge deposition in sluggish rivers, reservoirs and estuaries. For a synopsis of the field of sedimentation, see the following publications: Fluvial Sediments, A Summary of Source, Transportation, Deposition, and Measurement of Sediment Discharge, Colby, B. R., 1963, U.S. Geological Survey Bulletin 1181-A; Determination of Fluvial Sediment Discharge, Report No. 14, Water Resources Council, Interagency Subcommittee on Sedimentation, 1963.

Very slight differences in density are sufficient to cause thermal stratification in quiescent water bodies, but stratification stability also depends on water movement and depth. Stable stratification is common in lakes and reservoirs where there is a specific gravity difference of about .001 or .002 between waters of the upper layer (epilimnion) and lower layer (hypolimnion) (22,80). Such stratification inhibits vertical mixing and oxygen transfer to lower waters.

In stratified reservoirs, cool, incoming waters may travel almost directly to the dam outlet in a density current at a depth of compatible specific gravity. This reservoir characteristic is important in predetermining release temperatures and in selecting optimum discharge elevation.

Evaporation rate increases as water temperature rises elevate water vapor pressure. Evaporation is caused by the wind and the difference in water vapor pressure between the air and the water. This is expressed mathematically as:

$$F = \frac{CW}{L} (e_s - e_a)$$

where F = evaporation flux ($\text{lb ft}^{-2} \text{ day}^{-1}$)

L = latent heat of vaporization (BTU lb^{-1})

C = empirical evaporation coefficient

W = wind speed (mph)

e_s = water vapor pressure of saturated air at the temperature of the water surface (mm Hg)

e_a = water vapor pressure of overlying air (mm Hg)

The effect of changing water temperatures on evaporation rates can be shown by holding all terms constant except e_s:

$L = 1050$ BTU lb^{-1}

$C = 11.4$ (Lake Hefner coefficient (27,p.35))

$W = 10$ mph

$e_a = 7.5$ mm Hg (for an air temperature of 70°F with a relative humidity of 40%

$$F = \frac{(11.4)(10)(e_s - 7.5)}{(1050)} = 0.11(e_s - 7.5)\ \frac{lb}{ft^2\ day}$$

Solving this equation for various water temperatures, i.e., various e_s values, gives the following table:

Water Temperature (°F)	e_s (mm Hg)	F ($lb\ ft^{-2}\ day^{-1}$)
50	9.2	0.19
60	13.3	0.64
70	18.8	1.24
80	26.2	2.06
90	36.1	3.15

The values shown for evaporation flux (F) are specific for the given values of L, C, W and e_a. However, similar relative changes in F with respect to water temperature will occur for other values of the independent variables.

Most living organisms depend on oxygen in one form or another to maintain their life and reproductive processes; thus an adequate supply of oxygen must be available for any healthy aquatic environment. Hence, the relation of water temperature to gas solubility is a very important aspect of thermal pollution. Oxygen does not react chemically with water. Therefore, its solubility is directly proportional to its partial pressure at any given temperature under equilibrium conditions with the atmosphere. The effect of temperature on the solubility of oxygen in fresh water under one atmosphere of pressure is shown in Table 4.

Temperature changes cause complicated adjustments in the dynamic oxygen balance in waters and compound the difficulty of relating dissolved oxygen and other factors to oxygen demand, atmospheric reaeration, photosynthetic production, diffusion, mixing, etc. However, Phelps (57) states that "very few waters in nature carry a full quota of dissolved oxygen." Thus, general temperature rises, which decrease the oxygen holding capacity, may limit oxygen quantities which are already less than optimum.

Atmospheric nitrogen, with a solubility about one-half that of oxygen, is usually not considered an important control parameter for water quality. However, recent evidence on the Columbia River indicates that fish may be seriously affected in waters which have become supersaturated with nitrogen through rapid warming or pressure reduction after dam discharge.

CHEMICAL

Many factors affect chemical reactions, including the nature and concentration of reacting substances, catalytic influence, and temperature. The last named is important because chemical changes speed up as the temperature rises. In general, the speed of a chemical change is approximately doubled for each 10°C (18°F) rise in temperature (42,71).

In an irreversible reaction, higher temperatures will decrease the time required to produce the final products. In a reversible reaction, the process is complete when the reactants reach a point of dynamic stability, i.e., when the rate of forward reaction equals the rate of reverse reaction. In this case, temperature influences both the length of time required to reach equilibrium and the proportion of reactants and products at equilibrium conditions.

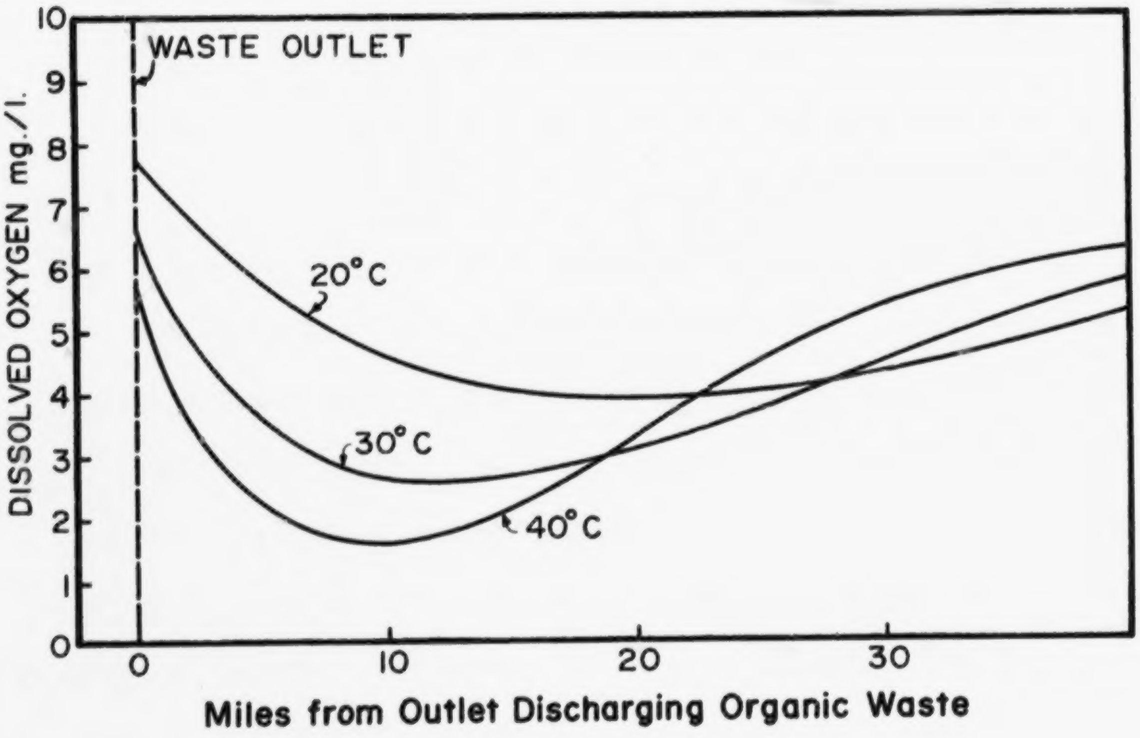
Most of the chemical effects on water quality, which are influenced by temperature, center around microbial activity. Any chemical reaction or change that results from a life process is properly termed a biochemical reaction. The majority of chemical reactions that organisms bring about occur through catalytic action at far lower temperatures than would be needed in the absence of catalysts. Such catalysts are known as enzymes, and are themselves temperature-sensitive. The rate of microbial activity increases, to a point, with the rates of chemical reactions. The majority of organisms affecting chemical water quality are in the mesophylic classification and thrive in a temperature range of 10 to 40°C (18 to 104°F). For this group, activity usually reaches a maximum between 30 and 37°C (86 and 99°F), then falls off as enzymes become less active.

Taste and odor problems induced by temperature-accelerated chemical or biochemical action are accentuated when oxygen is depleted. Substances which may accumulate include hydrogen sulfide, sulfur dioxide, methane, partially oxidized organic matter, iron compounds, carbonates, sulfates, and phenols, to list a few. In addition to the greater amounts of such substances, tastes and odors are usually more noticeable in warmer water due to decreased solubility of gases.

Biodegradable organic material entering water exerts a biochemical oxygen demand (BOD) which must be satisfied before assimilation of the material is completed. When the temperature of such a receiving water rises, the intensified action of microorganisms causes the BOD to be satisfied in a shorter distance from the discharge than would be accomplished at a lower temperature. Figure 1 depicts oxygen sag curves for a stream in which all conditions, i.e., streamflow, wasteflow, BOD of the waste, and initial percent DO saturation, were held constant, except temperature. It is apparent from the curves that the deoxygenation effect caused by waste assimilation is exerted over a shorter stream distance at higher temperatures; also that oxygen depletion occurs to a greater extent, since the sag point is lower at elevated temperature. Hence, it is possible that the discharge of an organic waste that previously had not caused excessive oxygen depletion could pose problems at an elevated temperature (26).

FIGURE I (26)

RELATION BETWEEN TEMPERATURE AND OXYGEN PROFILE
(After La Berge)



Chemical effects of slightly increased temperatures may have minor beneficial influences on water treatment. Disinfectant action is generally more rapid at higher temperatures. For example, for a given dose of free chlorine, the period required to disinfect water at 46°F is more than nine times greater than at 104°F (18). Reports on coagulant dosages are contradictory, although a report from the Commonwealth of Pennsylvania indicated a savings of 30 to 50¢ per million gallons per each 10°F rise in temperature (56). In any case, the potential beneficial effects must be weighed against the undesirable effects such as induced slime or algae growth, taste and odor problems, or unpalatable drinking water temperatures (7,39).

BIOLOGICAL

Water Temperature Criteria

On April 1, 1968, the National Technical Advisory Committee on Water Quality Criteria to the Federal Water Pollution Control Administration published its Report on Water Quality Criteria (76). Among the water quality parameters considered by this distinguished panel was temperature. The Committee produced recommendations with regard to water temperature for both freshwater organisms and marine and estuarine organisms. These recommendations, based on the best available information, indicate the temperature levels which will ensure the future growth and development of aquatic organisms. The Committee's recommendations are as follow:

Fresh Water Organisms (76, pp. 42,43)

"Recommendation for Warm Waters: To maintain a well-rounded population of warm-water fishes, the following restrictions on temperature extremes and temperature increases are recommended:

"(1) During any month of the year, heat should not be added to a stream in excess of the amount that will raise the temperature of the water (at the expected minimum daily flow for that month) more than 5 F. In lakes and reservoirs, the temperatures of the epilimnion, in those areas where important organisms are most likely to be adversely affected, should not be raised more than 3 F above that which existed before the addition of heat of artificial origin. The increase should be based on the monthly average of the maximum daily temperature. Unless a special study shows that a discharge of a heated effluent into the hypolimnion or pumping water from the hypolimnion (for discharging back into the same water body) will be desirable, such practice is not recommended.

"(2) The normal daily and seasonal temperature variations that were present before the addition of heat, due to other than natural causes, should be maintained.

"(3) The recommended maximum temperatures that are not to be exceeded for various species of warm water fish are given in table III-1.

"Recommendations for Cold Waters: Because of the large number of trout and salmon waters which have been destroyed, or made marginal or nonproductive, the remaining trout and salmon waters must be protected if this resource is to be preserved:

"(1) Inland trout streams, headwaters of salmon streams, trout and salmon lakes and reservoirs, and the hypolimnion of lakes and reservoirs containing salmonids should not be warmed. No heated effluents should be discharged in the vicinity of spawning areas.

"For other types and reaches of cold-water streams, reservoirs, and lakes, the following restrictions are recommended:

"(2) During any month of the year, heat should not be added to a stream in excess of the amount that will raise the temperature of the water more than 5 F (based on the minimum expected flow for that month). In lakes and reservoirs, the temperature of the epilimnion should not be raised more than 3 F by the addition of heat of artificial origin.

TABLE III-1

(Provisional maximum temperatures recommended as compatible with the well-being of various species of fish and their associated biota.)

93 F:	Growth of catfish, gar, white or yellow bass, spotted bass, buffalo, carpsucker, threadfin shad, and gizzard shad.
90 F:	Growth of largemouth bass, drum, bluegill, and crappie.
84 F:	Growth of pike, perch, walleye, smallmouth bass, and sauger.
80 F:	Spawning and egg development of catfish, buffalo, threadfin shad and gizzard shad.
75 F:	Spawning and egg development of largemouth bass, white, yellow, and spotted bass.
68 F:	Growth or migration routes of salmonids and for egg development of perch and smallmouth bass.
55 F:	Spawning and egg development of salmon and trout (other than lake trout).
48 F:	Spawning and egg development of lake trout, walleye, northern pike, sauger, and Atlantic salmon.

NOTE: Recommended temperatures for other species, not listed above, may be established if and when necessary information becomes available.

"(3) The normal daily and seasonal temperature fluctuations that existed before the addition of heat due to other than natural causes should be maintained.

"(4) The recommended maximum temperatures that are not to be exceeded for various species of cold-water fish are given in table III-1.

"NOTE: For streams, total added heat (in BTU's) might be specified as an allowable increase in temperature of the minimum daily flow expected for the month or period in question. This would allow addition of a constant amount of heat throughout the period. Approached in this way for all periods of the year, seasonal variation would be maintained. For lakes the situation is more complex and cannot be specified in simple terms.

Marine and Estuarine Organisms (76, pp. 69-70)

"Recommendation: In view of the requirements for the well-being and production of marine organisms, it is concluded that the discharge of any heated waste into any coastal or estuarine waters should be closely managed. Monthly means of the maximum daily temperatures recorded at the site in question and before the addition of any heat of artificial origin should not be raised by more than 4 F during the fall, winter, and spring (September through May), or by more than 1.5 F during the summer (June through August). North of Long Island and in the waters of the

Pacific Northwest (north of California), summer limits apply July through September, and fall, winter, and spring limits apply October through June. The rate of temperature change should not exceed 1 F per hour except when due to natural phenomena.

"Suggested temperatures are to prevail outside of established mixing zones as discussed in the section on zones of passage."

General

Water temperature plays a major role in the ability of any water-based ecological system to maintain optimum characteristics throughout all biological stages. Temperature effects on all organisms in an aquatic community are important because of the interdependence of species. For example, temperatures which are not lethal to fish or shellfish may affect metabolism, reproduction and growth, as well as reduce important food organisms, thereby inducing a change in the balance of the entire system. All natural biological systems are highly complex; hence it is very difficult and potentially misleading to generalize on the effect temperature changes have on the aquatic biota. A more realistic approach is to direct investigations to locally important species.

The scientific literature contains a large volume of information on the effect of temperature on all levels of the aquatic biota. Data are given which indicate maximum temperatures, optimum temperature ranges, maximum permissible temperature changes, acclimation temperatures, etc., for a wide variety of organisms. These data are based upon both laboratory and field investigations of various degrees of depth. A report on Temperature and Aquatic Life (71) by FWPCA's Technical Advisory and Investigations Branch, Cincinnati, Ohio, covers the important known effects which temperature has on aquatic biota.

The information presented on the biological effects of thermal pollution is not complete. Hopefully, however, it will be useful in detecting potential biological problems associated with water temperature changes. Where such problems are anticipated, a complete analysis of the situation, tailored to the specific site and problem, is needed.

Fish Life

The physiology of fishes is directly affected by temperature. Fishes are classed as poikilothermic animals, i.e., their body temperatures follow changes in environmental temperatures rapidly and precisely. In such animals, the factors favoring heat loss tend to equal the factors producing body heat, and thus the body approaches environmental temperature (59). In a majority of fishes, the body temperature differs by only 0.5 to 1.0^{o}C (0.9 to 1.8^{o}F) from that of the surrounding water (52). Therefore, a fundamental requirement of fishes is that the external temperature be well suited to internal tissue functionality (8).

The single most important point in analyzing or predicting the effects of temperature change on a fishery is to look at the individual species important to the specific water body under study. The following discussions are presented primarily to give insight to how and why changes in thermal regimen affect fish. To analyze specific cases, the worker is referred to the literature on specific species.

General

Metabolism.--Rates of metabolism and activity increase with increasing temperature. For example, according to van't Hoff's law, metabolic activity can double or even triple over a 10°C (18°F) rise in temperature. This increase in metabolic rate and activity will occur over most of the tolerated temperature range and then often cease suddenly near the upper lethal temperature. The rates of increased activity vary with different species, metabolic processes, and temperature ranges or levels. The rates may also be modified by salinity and oxygen factors (43). Changes in metabolic rates caused by temperature changes may be signaling factors for spawning or migration (52). Chemical reactions within the fish's body cells may be accelerated by temperature increases. Temperature-induced changes in cell chemistry are associated with four possible death mechanisms: 1) enzyme inactivity caused by the acceleration of the enzyme reaction to such a state that the enzyme is no longer effective, 2) coagulation of cell proteins, 3) melting of cell fats, and 4) reduction in the permeability of cell membranes (58). Cells may also be killed by the toxic action of the products of metabolism (28).

Reproduction.--The temperature range within which many fishes reproduce is narrower than that required by the majority of functions. Fishes generally spawn when a certain temperature level is reached. Of course, this level varies from species to species. Some fish spawn on a drop in temperature, while others respond to a rise in temperature (36). Even though the temperature requirements for breeding are narrow, fishes may populate a heated area by continued migration from the outside (51).

Development.--Temperature changes affect fish development in several ways. Abnormal temperatures can affect embryonic development. Low temperatures may slow down development, but in some cases fish attain a larger final size because of their slow, long-continued growth rather than the rapid growth experienced at higher temperatures (43).

Distribution.--Temperature is one of the more important factors governing the occurrence and behavior of fish life; it affects the general location of a given species and may also modify the species composition of a community or an ecosystem (43,78,36). Tropical and subtropical fishes are more stenothermal (tolerant of a narrow temperature range) than fishes of higher latitudes, and marine forms are more stenothermal than those found in fresh water (52). Some cold-water stenothermal forms may be eliminated by heated discharges, while the effect on some eurythermal (tolerant of a wide temperature range) species may be to increase the population (51). In tropical areas, species live close to their upper thermal limits, thus the effect of a thermal discharge can be quite severe. However, in northern areas, species may live in temperatures as much as 16°C (28.8°F) below their upper lethal temperature and not be as severely affected. Laboratory tests (8) have shown that a slow rate of decrease in environmental temperature is more important for maintaining life than a slow rate of increase. Lethal cold can be more important than lethal heat as a factor limiting the distribution of marine fish and as a hazard to some in their native habitats (25).

Synergistic Action.--Synergism is defined as the simultaneous action of separate agents which, together, have a greater total effect than the sum of their individual effects. In reference to water temperatures, synergistic action refers to the fact that temperature rises increase the lethal effect of toxic substances to fish and may also increase the susceptibility of the fish to many diseases. For example, a 10°C (18°F) rise in temperature doubles the toxic effect of potassium cyanide, and an 8°C (14.4°F) rise triples the toxic effect of O-xylene (45). It must be realized, however, that since the temperature effect on toxicity varies with each substance and with concentrations of any specific material, no hard and quick rule may be formulated to determine this temperature effect (45). Since domestic and industrial wastes are numerous in our nation's waters, the synergistic action between temperature and toxicity is a relatively common occurrence. Fish kills have accompanied small temperature rises which might have been relatively harmless in an unpolluted stream free of toxic substances (45). Thus, the concentration of a substance may be harmless at one temperature, but may contribute to fish mortalities when combined with the stress imposed by higher temperatures. Also, the virulence of fish pathogens may be increased by higher temperatures. For example, the myxobacteria *Chondrococcus columnaris*, which can cause death through tissue destruction, becomes more virulent as temperature is increased (68).

Dissolved Oxygen.--Two factors associated with rising water temperatures are decreases in available oxygen and increases in metabolic rates. These factors combine to render the aquatic environment less compatible to fish life at high water temperatures. At low water temperatures in the range of 0 to 4^{o}C (32 to 39.2^{o}F), a dissolved oxygen level of one to two mg/l is sufficient for survival of many freshwater fish species. When the temperature reaches 15 to 20°C (59 to 68°F), less than three mg/l of dissolved oxygen is often lethal. At these temperatures, oxygen levels as high as five mg/l are sometimes required to support minimum activity. Safe or acceptable levels may be even higher in order to support normal activity beyond that of merely staying alive.

Acclimation.--The temperature to which fish become adjusted over an extended period of time, i.e., the acclimation temperature, is important because of its influence on lethal temperature levels. The capacity to acclimate depends on the genetic background, environmental history, physiological conditions, and age of the organism involved (43). For example, the resistance of animals to cold is much more variable than resistance to heat, and resistance to cold varies with size, smaller fish resisting best (36). Acclimation to different temperatures may involve changes in orientation, migration, and other behavioral aspects such as territorialism and biological rhythms (43). Gradual temperature changes are tolerated much better than sharp changes. Brief or intermittent exposure to high temperature can result in markedly increased resistance to heat which is not readily lost on subsequent exposure to low temperature (25). However, it is the rapid onset of low temperatures that probably causes death, outstripping the ability of fish to acclimate and resulting in greater mortalities (9). Deaths resulting from the inability of fish to rapidly acclimate to lowering temperatures have been reported (34,37). Acclimation to low temperature usually tends to shift the lower thermal limit downward, and acclimation to high temperatures tends to shift the upper limts upward (43). Thus, the ability to acclimate affects the temperature range that a fish can tolerate. Fish acclimated to cold winter temperatures are often subjected to lethal temperatures in the spring as warmer water is encountered (71).

Freshwater Fishes

Maximum Temperatures.--Maximum temperatures have been determined for numerous species of freshwater fish. These temperatures indicate the highest temperature at which a fish can survive, but they are often higher than the maximum temperature at which a species can survive for long periods. Thus, maintaining water temperature at these maximums does not insure the maintenance of a fish population.

Table 5 shows maximum and minimum temperatures for various species and acclimation temperatures (71,56). Values shown are LD_{50} temperatures, i.e., temperatures survived by 50 percent of the test animals. These figures are based on specific test conditions, so care must be taken in interpreting the data, since temperature limits for a given species will vary slightly depending on the fish's rate of heating, size, and physiological condition.

TABLE 5 (71,56)

MINIMUM AND MAXIMUM TEMPERATURES FOR CERTAIN FRESHWATER FISHES

Fish	Acclimated To		Minimum Temperature*			Maximum Temperature*		
	°C	°F	°C	°F	Time,Hr.	°C	°F	Time,Hr.
Bass, largemouth	20.0	68.0	5.0	41.0	24	32.0	89.6	72
	30.0	86.0	11.0	51.8	24	34.0	93.2	72
Bluegill (*Lepomis macrochirus purpurescens*)	15.0	59.0	3.0	37.4	24	31.0	87.8	60
	30.0	86.0	11.0	51.8	24	34.0	93.2	60
Catfish, channel	15.0	59.0	0.0	32.0	24	30.0	86.0	24
	25.0	77.0	6.0	42.8	24	34.0	93.2	24
Perch, yellow	5.0	41.0	----	----	--	21.0	69.8	96
(winter)	25.0	77.0	4.0	39.2	24	30.0	86.0	96
(summer)	25.0	77.0	9.0	48.2	24	32.0	89.6	96
Shad, gizzard	25.0	77.0	11.0	51.8	24	34.0	93.2	48
	35.0	95.0	20.0	68.0	24	37.0	98.6	48
Shiner, common (*Notropis cornutus frontalis*)	5.0	41.0	----	----	--	27.0	80.6	133
	25.0	77.0	4.0	39.2	24	31.0	87.8	133
	30.0	86.0	8.0	46.4	24	31.0	87.8	133
Trout, brook	3.0	37.4	----	----	--	23.0	73.4	133
	20.0	68.0	----	----	--	25.0	77.0	133

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* Values are LD_{50} temperature tolerance limits, i.e., water temperatures survived by 50 percent of the test fish.

A temperature need not kill a fish directly for it to be lethal. Brook trout were found to be comparatively slow in catching food minnows at 17.2°C (63°F) and virtually incapable of catching minnows at 21°C (70°F). Thus, even though their lethal limit is 23 to 25°C (73.4 to 77°F) (Table 5), the fish could not survive in this temperature due to a lack of food (56).

Preferred Temperatures.--Most biologists agree that fish can live for short periods in waters of abnormally high temperatures, but at these high temperatures the fish cannot perpetuate their population. Thus, fish seek out the temperature that is best suited for their survival. This "preferred temperature" is given in Table 6 for several species of yearling fish based upon laboratory experiments (71,31). Table 7 shows the temperature at which fish in the natural environment seem to congregate, thus indicating their "preferred temperature" (71,31).

The level of thermal acclimation influences the range of temperatures preferred. In general, the difference between the acclimation temperature and the preferred temperature decreases as the acclimation temperature increases (31).

Competition between species is also important to distribution and survival since different species have different preferred temperatures. For example, temperatures higher than optimum may not kill trout, but they may produce environmental conditions favorable for the production of coarse fish and thus reduce the trout's food supply (70).

TABLE 6

THE FINAL PREFERRED TEMPERATURE FOR VARIOUS SPECIES OF FISH AS DETERMINED BY LABORATORY EXPERIMENTS

Species	Final Preferred Temperature °C	Final Preferred Temperature °F	Authority
Bass, largemouth	30.0-32.0	86.0-89.6	Fry, 1950
Bass, smallmouth	28.0	82.4	Fry, 1950
Bluegill	32.3	90.1	Fry & Pearson, 1952
Carp	32.0	89.6	Pitt, Garside & Hepburn, 1956
Muskellunge	24.0	75.2	Jackson & Price, 1949
Perch, yellow	24.2	75.6	Ferguson, 1958
" "	21.0	69.8	McCracken & Starkma, 1948
Trout, brook	14.0-16.0	57.2-60.8	Graham, 1948
Trout, brown	12.4-17.6	54.3-63.7	Tait, 1958
Trout, lake	12.0	53.6	McCauley & Tait, 1956
Trout, rainbow	13.6	56.5	Garside & Tait, 1958

Marine, Estuarine, and Anadromous Fishes

Spawning.--Limits of temperature requirements for spawning are usually much more stringent than for adult fish survival. For example, the normal spawning temperature for sockeye salmon is between 7.2 and 12.8°C (45 and 55°F) (63); lower and upper lethal limits are 0°C (32°F) and about 25°C (77°F), respectively. Pink salmon spawn best near 10°C (50°F) (65).

TABLE 7

PREFERRED TEMPERATURES FOR VARIOUS SPECIES OF FRESHWATER FISH BASED ON FIELD OBSERVATIONS

Species	Preferred Temperature °C	Preferred Temperature °F	Water Body	Location	Authority
Alewife	4.4- 8.8	39.9-47.8	Cayuga Lake	New York	Galligan, 1951
Bass, largemouth	26.6-27.7	80.0-81.9	Norris Res.	Tennessee	Dendy, 1948
Bass, rock	14.7-21.3	58.5-70.3	Lakes	Wisconsin	Hile & Juday, 1941
" "	20.7	69.3	Streams	S. Ontario	Hallam, 1958
Bass, smallmouth	20.3-21.3	68.5-70.3	Nebish Lake	Wisconsin	Hile & Juday, 1941
" "	21.4	70.5	Streams	S. Ontario	Hallam, 1958
Bass, spotted	23.5-24.4	74.1-75.9	Norris Res.	Tennessee	Dendy
Perch, yellow (small)	12.2	54.0	Muskellunge Lake	Wisconsin	Hile & Juday, 1941
Perch, yellow (large)	20.2-21.0	68.4-69.8	Lakes	Wisconsin	Hile & Juday, 1941
Shad, gizzard	22.5-23.0	72.5-73.4	Norris Res.	Tennessee	Dendy
Trout, brook	14.2-20.3	57.6-68.5	Moosehead Lake	Maine	Cooper & Fuller
" "	15.7	60.3	Streams	S. Ontario	Hallam, 1958
" "	12.0-20.0	53.6-68.0	Redrock Lake	Ontario	Baldwin, 1948
Trout, lake	10.0-15.0	50.0-59.0	Cayuga Lake	New York	Galligan, 1951
" "	14.0	57.2	White Lake	Ontario	Kennedy, 1941
" "	11.0-11.5	51.8-52.7	Moosehead Lake	Maine	Cooper & Fuller, 1945
" "	8.0-10.0	46.4-50.0	Louisa & Redrock Lakes	Ontario	Martin, 1952
Walleye	20.6	69.1	Trout Lake	Wisconsin	Hile & Juday, 1941
"	22.7-23.2	72.9-73.8	Norris Res.	Tennessee	Dendy, 1948

During migration salmon do not feed, so high water temperatures which increase their metabolic rate may result in fuel depletion before spawning can occur (33). Fish migration is hampered by unfavorable temperature conditions. A thermal block of 21.1°C (70°F) at the mouth of the Okanogan River, Washington, prevented migration into the stream from the Columbia River (45). Generally for salmon, upstream migration and reproduction occur best at temperatures between 7.2 and 15.6°C (45 and 60°F) (12).

Eggs.--The incubation of eggs and development of fry generally have more critical temperature requirements than either fingerling or adult fish. Table 8 shows the minimum and maximum temperatures reported for the successful hatching of various species of marine, estuarine, and anadromous fish eggs. Care must be taken not to equate successful hatching with fry survival; Chinook salmon eggs incubated at 16.1°C (61°F) hatched successfully, but suffered severe mortality in the late fry stage (54).

Young Fish.--Table 9 shows the temperature limits for the survival of various species of young marine, estuarine, and anadromous fishes at several acclimation temperatures. This information is based on laboratory tests which often produce data not directly transferable to the natural environment. For example, laboratory tests on striped bass fingerlings showed an upper lethal

TABLE 8

TEMPERATURE RANGES FOR SUCCESSFUL EGG HATCHING OF VARIOUS MARINE, ESTUARINE, AND ANADROMOUS FISHES

Species	Lower Limit		Upper Limit		Authority
	°C	°F	°C	°F	
Bass, striped	12.8	55.0	23.9	75.0	Albercht, 1964
California killifish	16.6	61.9	28.5	83.1	Hubbs, 1965
California grunion	14.8	58.6	26.8	80.1	Hubbs, 1965
Salmon, Chinook	5.8	42.4	14.2	57.6	Combs & Burrows, 1957
	9.4	48.9	14.4	57.9	Seymour, 1956
	5.6	42.1	14.4	57.9	Leitritz, 1962
Salmon, sockeye	4.4-5.8	39.9-42.4	12.8-14.2	55.0-57.6	Combs, 1965
Sea lamprey	15.0	59.0	25.0	77.0	McCauley, 1963
	15.6	60.1	21.1	70.0	Piavis, 1961

TABLE 9

LETHAL TEMPERATURE RANGES FOR YOUNG MARINE, ESTUARINE, AND ANADROMOUS FISHES

Species	Acclimation Temperature °C	Acclimation Temperature °F	Lower Lethal Temperature °C	Lower Lethal Temperature °F	Upper Lethal Temperature °C	Upper Lethal Temperature °F	Authority
Greenfish	12.0-28.0	53.6-82.4	4.1-13.0	39.2-55.4	28.7-31.5	83.7-88.7	Doudoroff, 1942
Herring	7.5-15.5	45.5-59.9	-1.8 to -0.75	28.8-30.7	22.0-24.0	71.6-75.2	Blaxter, 1960
Salmon, Chinook	5	41	----	----	21.5	70.7	Brett, 1956
" "	10	50	0.8	33.4	24.1	75.7	" "
" "	15	59	2.5	36.5	25.0	77.0	" "
" "	20	68	4.5	40.1	25.1	77.2	" "
" "	23	73.4	7.4	45.3	----	----	Brett, 1952
" "	--	----	----	----	26.7	80.0	Kerr, 1953
Salmon, chum	5	41	----	----	21.8	71.2	Brett, 1956
" "	10	50	0.5	32.9	22.6	72.7	" "
" "	15	59	4.7	40.5	23.1	73.6	" "
" "	20	68	6.5	43.7	23.7	74.7	" "
" "	23	73.4	7.3	45.2	----	----	Brett, 1952
Salmon, pink	5	41	----	----	21.3	70.3	Brett, 1956
" "	10	50	----	----	22.5	72.5	" "
" "	15	59	----	----	23.1	73.6	" "
" "	20	68	----	----	23.9	75.0	" "
Salmon, silver	5	41	0.2	32.4	22.9	73.2	Brett, 1956
" "	10	50	1.8	35.1	23.7	74.7	" "
" "	15	59	3.5	38.3	24.1	75.7	" "
" "	20	68	4.5	40.1	25.0	77.0	" "
" "	23	73.4	6.4	43.5	----	----	Brett, 1952
Salmon, sockeye	5	41	0.0	32.0	22.2	72.0	Brett, 1956
" "	10	50	3.1	37.6	23.4	74.1	" "
" "	15	59	4.1	39.4	24.4	75.9	" "
" "	20	68	4.7	40.5	24.8	76.6	" "
" "	23	73.4	6.7	44.1	----	----	Brett, 1952
Topsmelt	20	68	10.1	50.2	31.8	89.2	Doudoroff, 1942

temperature of 35°C (95°F), but studies in the Atlantic Ocean indicated striped bass fish kills occurring at temperatures of 25 to 27°C (77.0 to 80.6°F) (69).

Fish in the estuarine environment are more susceptible to temperature changes than those in fresh water. However, wider ranges of tolerance between species exists in estuarine waters. Decreases in temperature seem to have more of an effect on estuarine fishes than on freshwater fishes. In studies of young greenfish to determine the resistance and acclimation of marine fishes to temperature changes, Doudoroff (24) found that heat resistance was gained rapidly and lost slowly. Acclimation to decreasing temperatures was slower than acclimation to increasing temperatures. Transposed to the practical case, this fact implies that the shutdown of a power generating plant may be more detrimental than its normal discharge of heat.

Anadromous fingerlings have maximum growth in the temperature range of 10 to 15.6°C (50 to 60°F) (12). Research on the effects of temperature on swimming speed indicates that for young sockeye salmon optimum cruising speed occurred at 15°C (59°F), and for young silver salmon at 20°C (68°F) (10); thus, the fish's mobility for protection and feeding is affected by temperature changes.

Adult Fish.--Table 10 shows the lethal temperature limits for several species of adult marine, estuarine, and anadromous fishes.

TABLE 10

LETHAL TEMPERATURE LIMITS FOR ADULT MARINE, ESTUARINE, AND ANADROMOUS FISHES

Species	Acclimation Temperature °C	Acclimation Temperature °F	Lower Lethal Temperature °C	Lower Lethal Temperature °F	Upper Lethal Temperature °C	Upper Lethal Temperature °F	Authority
Alewife	---	---	---	---	26.7-32.2	80.0-90.0	Trembley, 1960
Bass, striped	---	---	6.0- 7.5	42.8-45.5	25.0-27.0	77.0-80.0	Talbot, 1966
California killifish	14.0-28.0	57.2-82.4	---	---	32.3-36.5	90.1-97.7	Doudoroff, 1942
Common silverside	7.0-28.0	44.6-82.4	1.5- 8.7	34.8-47.8	22.5-32.5	73.3-90.3	Hoff & Westman, 1966
Flounder, winter	21.0-28.0	69.8-82.4	1.0- 5.4	33.8-41.6	---	---	" " "
" "	7.0-28.0	44.6-82.4	---	---	22.0-29.0	71.6-84.2	" " "
Herring	---	---	-1.0	30.2	19.5-21.2	67.1-70.1	Brawn, 1960
Northern swellfish	14.0-28.0	57.2-82.4	8.4-13.0	47.1-55.4	---	---	Hoff & Westman, 1966
" "	10.0-28.0	50.0-82.4	---	---	28.2-33.0	82.9-90.4	" " "
Perch, white	4.4	40.0	---	---	27.8	82.0	Trembley, 1960
Salmon (general)	---	---	0.0	32.0	26.7	80.0	Columbia Basin Interagency Comm., 1966

Adult fish are usually able to select their preferred temperatures, unless trapped in shallow water or forced to migrate through thermal blocks. Adult anadromous fishes spend most of their life cycle in the ocean and enter fresh water only to migrate up a stream to spawn, where previously mentioned thermal conditions may affect them.

Shellfish

Most shellfish, such as clams, oysters, crabs and lobsters, which are directly beneficial to man as a food source, are marine, stenothermal organisms. Some species are stenothermal for one developmental stage and eurythermal for another. Generally, however, breeding and spawning requirements are stenothermal. The time of mollusc, e.g., clams, oysters, etc., spawning is temperature dependent. Most molluscs with specific temperature-breeding relationships spawn in the spring and summer, and many do not spawn until a certain temperature is reached (1). The American oyster *Crassostrea virginica* spawns at temperatures between 15 and 34°C (59 and 93.2°F) depending on its condition, and spawning is usually triggered by a rise in temperature (35).

Many species tolerate temperatures in excess of those at which breeding occurs. For example, the shore crab *Carcinus maenas* thrives, but does not breed, at temperatures of 14 to 28°C (57.2 to 82.4°F) (51). In this case, temperature limits the population, but migration of organisms can occur from outside the heated area.

Physiology, metabolism and development are all affected by temperature. The American oyster *C. virginica* ceases feeding at temperatures below 7°C (44.6°F). Above 32°C (89.6°F) ciliary activity, which is responsible for water movement, is decreased, and at 42.0°C (107.6°F) almost all body functions cease, or are reduced to a minimum. The European oyster *Ostrea lurida* tends to close its shell as temperatures drop. At 4 to 6°C (39.2 to 42.8°F) the oyster's shell remains closed most of the time. At 6 to 8°C (42.8 to 46.4°F) the shell opens for about six hours per day, and at 15°C (59°F) the shell stays open for 23 hours a day (35). Very little is known about the prolonged effects of temperatures above 32 to 34°C (90 to 94°F) on oysters; however, long exposure to such temperatures may impede the oyster's normal rate of water circulation. When either low or high temperatures cause shells to close or ciliary action to cease, oysters cannot feed and subsequently lose weight. Thus, temperature changes can produce an effect similar to chronic toxicity.

The distribution of benthic organisms is temperature dependent. The American oyster *C. virginica* is present in Gulf Coast waters that may vary between 4 and 34°C (39.2 and 93.2°F), but the European oyster *O. edulis* is restricted to water temperatures of 0 to 20°C (32 to 68°F) (36). The opossum shrimp *Neomysis americana* is not often found at temperatures above 31°C (87.8°F) in the Cheasapeake estuary (49).

Algae and Other Aquatic Plants

Successive changes from continual temperature increase may result in the elimination of desirable species along with the establishment of undesirable or nuisance organisms. Some species of algae and other aquatic plants are nuisances because they are unsightly or produce undesirable tastes and odors. In addition, the biological oxygen demand of the dead cells depletes dissolved oxygen resources. Blue-green algae are especially undesirable from the standpoint of taste and odor problems in municipal water supplies.

There appear to be particular temperature ranges that are tolerated by each algal species and by closely related species or groups of species. For example, in an unpolluted stream, diatoms grow best at 18 to 20^{o}C (64.4 to 68^{o}F); green algae at 30 to 35^{o}C (86 to 95^{o}F); and blue-green algae at 35 to 40^{o}C (95 to 104^{o}F) (15). If temperatures are increased from 10 to 38^{o}C (50 to 100.4^{o}F), the predominant species groups change correspondingly from diatoms to green algae to blue-green algae (77). Some of the more high-temperature-tolerant species belonging to algal groups other than the blue-green may persist with the predominant blue-greens at increased temperatures, and several less tolerant species of the blue-green algae may succumb with the diatoms and green algae as the temperature rises.

Benthos

Studies of particular species of benthic macro-invertebrates have indicated that lethal temperatures vary considerably with the type of organism. Laboratory investigations on the freshwater snail *Lymnaea stagnalis* showed a lethal temperature of 30.5°C (89.6°F) (53), while the species *Viviparus malleatus* did not succumb until the temperature reached 37.5°C (99.5°F) (40).

Field work on rivers has indicated that benthic organisms decrease in number when water temperature exceeds 30°C (86°F) (67). The macro-invertebrate riffle fauna of the Delaware River has decreased due to heated water discharges. At 35°C (95°F) many caddisfly, *Hydropsyche*, were dead, and those which remained alive were extremely sluggish. This study suggests that there is an upper tolerance level near 32.2°C (90°F) for a variety of different benthic forms with extensive losses in numbers and diversity accompanying a further increase in temperature (20).

Bacteria

In discussing the effect of temperature changes on bacteria, it is important to distinguish between rapid changes, which may induce thermal shock, and slow, gradual changes. Organisms can adapt to gradual changes in the environment; however, such adaptation may take several life cycles, i.e., each successive generation is better adapted to its environment. Since bacteria have very short life cycles, many generations may occur within a relatively short time. If a gradual temperature increase occurs over several life cycles, then each successive generation is subjected to only a small portion of this total temperature increase. Thus, bacteria can adapt to slow temperature changes more easily than higher forms such as fish.

The relationships of temperature to microorganism growth and survival are very complex. Bacteria can be grouped according to their temperature requirements for growth:

<20°C (68°F) - psychrophiles
20 to 55-65°C (68 to 131-149°F) - mesophiles
>55-65°C (131-149°F) - thermophiles

The majority of bacteria are mesophilic. Many found in natural waters are saprophytes, i.e., organisms that live on preformed organic matter, which have optimum temperatures of 22 to 28°C (70 to 82°F). Parasitic bacteria have optimum temperatures near 37°C (98.6°F) and include those microorganisms pathogenic to man. Changes in temperature have a large effect on these organisms' rate of activity.

The effect of temperature on bacteria cannot always be considered separately from other environmental factors. Some species are more abundant in winter, while others abound in the summer when different environmental conditions are encountered (13).

Rising stream temperatures can be favorable for those bacteria which multiply in water by inducing the recurring cycles of life and death more rapidly (61). Higher temperatures in an organically polluted stream generally result in increased bacterial numbers, and low temperatures are not conducive to rapid growth. Temperatures of 1 to 8°C (33.8 to 46.4°F) may suppress growth and multiplication, but bacteria persist longer at these cool temperatures.

Increases in bacterial populations are not necessarily harmful. For example, those bacteria which play an active role in stream self-purification do perform a useful function. These include the bacteria which aerobically oxidize organic material, as well as those responsible for nitrification and anaerobic decomposition of bottom sediments. However, increases in pathogenic bacteria should always be avoided.

Bacterial slimes cause unsightly scums and foul fishing nets. Rivers carrying a high organic load often develop such deleterious slime growths at low temperatures. A study on the Columbia River indicated that Sphaerotilus slime grows best at 10 to 15°C (50 to 59°F). Growth ceases below 4°C (39.2°F). Infestation of Sphaerotilus may occur below 10°C (50°F), given sufficient time (2). Beds of Sphaerotilus slime extend farther downstream from a waste outfall during the winter than in the summer, because warmer temperatures may inhibit the organism's food conversion efficiency (23), or because of competition for food from other microorganisms.

A recent study on the survival of bacterial indicators of pollution showed that, the lower the temperature, the longer the survival (17). Table 11 shows the average time for 99% reduction in original titers of microorganisms from three sources (17).

In summary, the temperature of natural waters, even during the summer, is usually below the optimum for pollution-associated bacteria. Increasing the water temperature increases the bacterial multiplication rate when the environment is favorable and the food supply is abundant. Increasing temperature within the growth range causes a more rapid die-off when the food supply is limited.

TABLE 11

AVERAGE TIME IN DAYS FOR 99.9% REDUCTION IN ORIGINAL TITER OF MICROORGANISMS AT THREE TEMPERATURES FROM THREE SOURCES

	Little Miami River			Ohio River			Sewage		
	28°C (82.4°F)	20°C (68°F)	4°C (39.2°F)	28°C (82.4°F)	20°C (68°F)	4°C (39.2°F)	28°C (82.4°F)	20°C (68°F)	4°C (39.2°F)
A. aerogenes	6	8	15	15	18	44	10	21	56
E. coli	6	7	10	5	5	11	12	20	48
S. fecalis	6	8	17	9	18	57	14	26	48

CONTROL

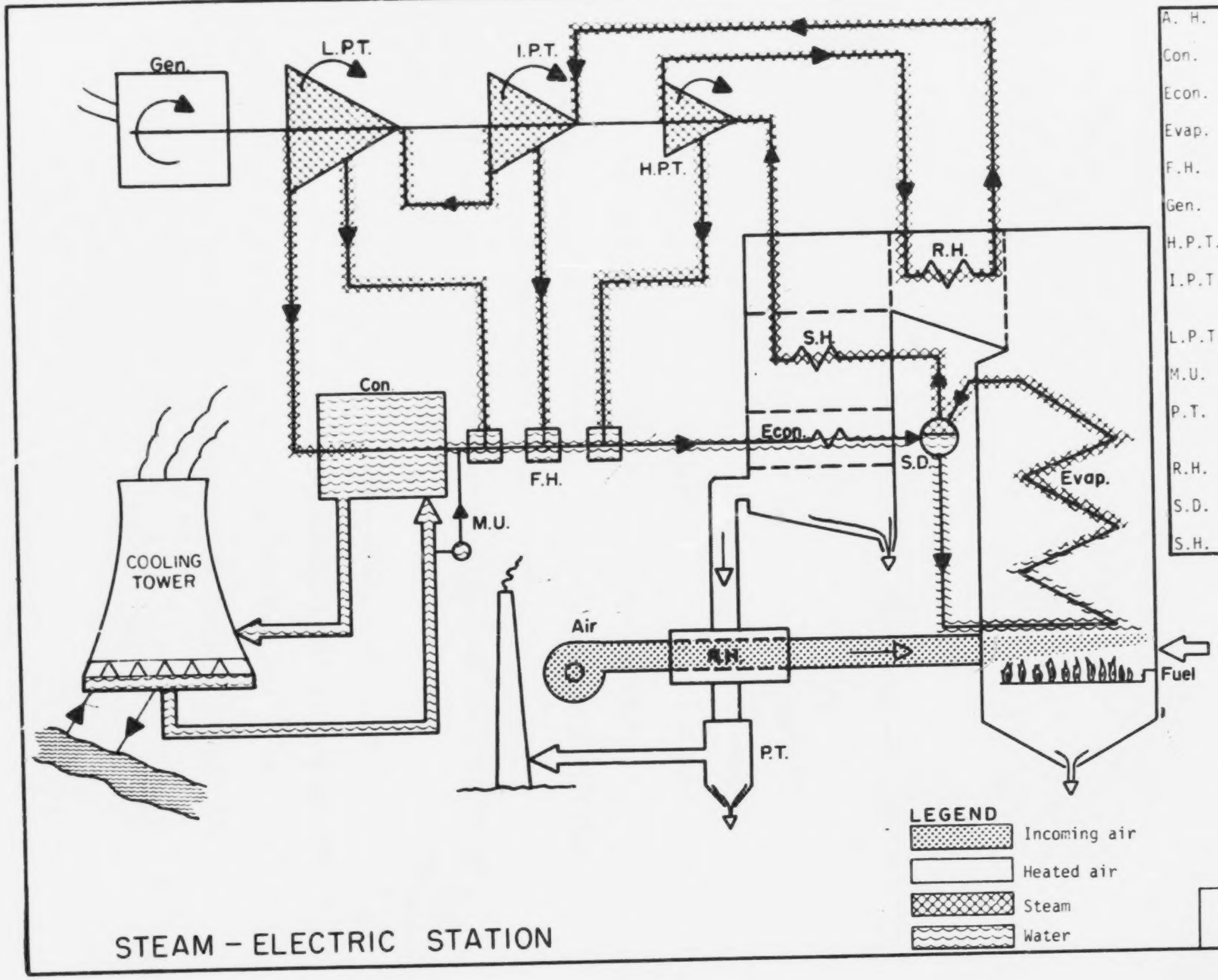
PROCESS CHANGES

Increased Efficiencies

The adage about prevention and cure applies as well to waste heat as to anything else. Reduction of waste heat production is desirable for two reasons: 1) less waste of expensive energy, and 2) fewer problems with or after disposal. Upgrading the efficiency of operations which produce heat as a by-product is, therefore, a logical starting point when considering control of thermal pollution.

Efficiency gains in fossil-fueled, steam-electric stations have reduced their waste heat discharge rate by approximately one-half over the past 30 years (Table 3). Such gains have been accomplished through a number of refinements in the plant itself and in operating conditions. Figure 2 presents a schematic diagram of the basic components of a fossil-fueled steam-electric plant which may be referred to for a better understanding of plant operation and efficiency.

The basic steam plant cycle is as follows: the steam drum furnace combination turns water into high-pressure steam, which is carried to the turbines at a speed of about 200 miles per hour. Within 1/30th of a second the steam rushes through the turbines,


Gen.
L.P.T.
I.P.T.
H.P.T.
R.H.
S.H.
Con.
Econ.
S.D.
F.H.
Evap.
M.U.
COOLING TOWER
Air
A.H.
Fuel
P.T.
LEGEND
Incoming air
Heated air
Steam
Water

A. H.	Air Heater
Con.	Condenser
Econ.	Economizer
Evap.	Evaporator
F.H.	Feedwater Heater
Gen.	Generator
H.P.T.	High Pressure Turbine
I.P.T.	Intermediate Pressure Turbine
L.P.T.	Low Pressure Turbine
M.U.	Make-up (water)
P.T.	Electrostatic Precipitator
R.H.	Reheater
S.D.	Steam Drum
S.H.	Super Heater

STEAM - ELECTRIC STATION

FIGURE 2

traveling through a series of stationary nozzles and revolving buckets which spin the turbine rotor and connected generator shaft at either 1800 or 3600 revolutions per minute.

Drastic changes occur in the steam as it releases its energy to the rotating buckets. Steam may enter the turbines at temperatures of over 1000°F and leave at less than 100°F. It enters at a pressure of 2000 or more psi, expands to a thousand times its entrance volume, and leaves at a pressure less than atmospheric.

From the turbine exhaust the expanded, low-pressure steam goes to the condenser, where it is cooled until it condenses to water. The process reduces the volume of the steam by a factor of 27,000 in a near-perfect vacuum, thereby returning it to a state in which it can be easily handled. The water is returned to the boiler through the feedwater heaters to be used over and over again as the cycle continues endlessly.

As the cycle repeats, it is necessary to continuously remove from the condenser an amount of heat equal to that given up in converting exhaust steam into water. Plant and operational refinements reduce the amount of heat entrained in exhaust steam which, in effect, increases the overall plant thermal efficiency. Reduction of exhaust heat is attained through several methods (44):

1) Increasing steam pressure--Elevating the steam pressure at the turbine entrance reduces exhaust heat by varying increments, but in general a 100 psi pressure increase will reduce exhaust heat

per unit of electricity by 0.4%.

2) Superheating steam--Steam generated in the boiler is heated even more in a superheat section of the furnace. Each 50°F additional temperature rise reduces exhaust heat per unit of electricity by about 1.4%.

3) Reheating steam--After the steam has passed through the high-pressure turbine section it is returned to the furnace reheat section to absorb additional heat energy. Again, each 50°F increase here reduces exhaust heat per unit of electricity by about 1.4%.

4) Boiler feedwater heating--A portion of the steam is withdrawn before it reaches the final turbine exhaust, thereby eliminating its passage through the condenser. This steam is utilized to increase the temperature of water entering the boiler. Feedwater heating can reduce exhaust heat up to 37% per unit of electricity, depending on the number of heaters used.

5) Reducing exhaust pressure--The pressure in the condenser is transmitted to the turbine exhaust, i.e., turbine backpressure. This pressure influences heat rejection to the extent that each 1 psi reduction in pressure reduces exhaust heat per unit of electricity by 2.5%.

Modern power plants are designed to make use of these efficiency refinements as much as possible. Through such techniques, new fossil-fueled plants attain efficiencies near 40%; nuclear-fueled plants about 33%.

Nuclear-fueled plants are inherently less efficient than fossil-fueled plants even though they too utilize the basic steam cycle to spin turbines and generate power. The major factor in the efficiency limitation is that imposed through reduced operating temperatures. Technological difficulties make it impractical, uneconomical, or unsafe to produce high-pressure, superheated steam in a water-cooled reactor system. Whereas modern fossil-fueled plants utilize steam at temperatures near 1050^{o}F and pressures over 3000 psi, nuclear-fueled reactors of the boiling water or pressurized water types produce steam at about 600^{o}F and about 1000 psi or 2000 psi, respectively.

Lower temperatures and pressures imply less energy content per unit volume of steam. Hence, nuclear-fueled plants, compared to fossil-fueled plants, require larger turbines and condensers for a given generating capacity in order to compensate for the lower quality of steam used.

The principal advantage of nuclear fuel is its tremendous energy density. One ton of uranium has the energy potential of three million tons of coal. Present-day reactors convert only about 0.5% of this energy to usable heat, i.e., combustion efficiency is 0.5%. Advanced reactor design, i.e., breeder types, will convert much more energy into a useful form (66). However, while advanced designs will improve fuel consumption, they will not necessarily increase the thermal efficiency to reduce waste heat in steam-electric plant operation.

Reduction of waste heat output from nuclear plants will depend on development of advanced converters which will allow higher operating temperatures. Such converters will employ a reactor coolant other than water in the primary flow loop, which circulates fluid through the reactor core for heat absorbtion. The heat is then transferred to steam through a heat exchange process in a steam generator. Systems of this type, still in developmental stages, are using fluids such as helium, liquid sodium or liquid potassium for coolants. Reactor outlet temperatures of over 1000°F are possible.

Because of the vast energy stores in nuclear fuel, its utilization for power production is inevitable. For the next 15 to 20 years, the number of plants in the 30% efficiency class will increase rapidly, which indicates that more efficient systems will surely lag behind our demands for power. This being the case, our immediate efforts must focus on waste heat utilization and dissipation while technology is being developed for more efficient power production methods.

New Methods

Gas turbines offer a means of power production without cooling water. Air is taken from the atmosphere, compressed, and subsequently burned with a liquid or gaseous fuel. The resulting high-temperature, high-pressure gases expand through a power turbine and then exit to the atmosphere.

Today's gas turbine efficiencies of less than 25% are not competitive for power production on a large scale, although some relatively small turbines are being used for standby and peaking operation. Future development may achieve higher operating temperatures and increased air flow, which in turn would increase efficiency to a level near that of fossil-fueled steam plants.

Heat exhausted from gas turbines might possibly be put to use in a conventional steam-electric plant. Such a combination would reduce the waste heat discharge rate, although cooling water would still be used.

Other systems currently under development may offer promise for future bulk power generation without the need for cooling water. Two systems receiving much attention lately are fuel cells and magnetohydrodynamics (MHD), which would convert heat energy directly into electrical energy (38).

Fuel cells are somewhat similar to conventional storage batteries in that they consist of two electrodes separated by an electrolyte. The fuel cell does not contain a store of energy; it generates current as long as fuel and oxidant supply chemical energy for conversion to electricity.

Individual fuel cells produce very small quantities of power. Hence, thousands of cells would have to be connected in groups to increase power output to a level which would permit large-scale production. Predicted eventual efficiencies of 50 to 85% is a further attribute of the fuel cell system. A prototype and larger scale central station fuel cell plant are being developed by Westinghouse under a contract from the Office of Coal Research, Department of the Interior. Target dates for construction of the two plants are 1969 and 1973, respectively (38).

MHD generators utilize the principle of passing a conductor through a magnetic field to produce current. In this system the moving conductor is an ionized gas. Very high temperatures and gas velocities must be maintained, which at the present time presents some major technical difficulties. In theory, the application of a MHD generator can be visualized, possibly in combined operation with a conventional steam plant, but major advances in materials must be achieved before the future of MHD power generation can be predicted (38).

ENERGY UTILIZATION

The optimum solution to problems associated with waste heat disposal would be the use of rejected heat for beneficial purposes. When dealing with power plant discharges, however, one is confronted with immense quantities of water which are of low quality when considered as a heat source. Utilization of waste heat in this form is therefore restricted to only a very few possible applications.

One potential for such utilization is aquiculture, the farming of plants or animals in fresh or salt water. Aquiculture has been successfully practiced in Japan and elsewhere. Heated discharges could be used to enhance the environment and increase production of commercially valuable species such as pompano, catfish, shrimp, oysters, and scallops. Research, development, and pilot studies are in progress to determine the feasibility of such cultivation in American waters (50).

Some nuclear plants could possibly be located to provide beneficial use of heated discharges in keeping shipping lanes free from ice for extended seasons. A recent journal article (5) contained specific recommendations for such application to the St. Lawrence Seaway, proposing extension of the shipping season to the end of December or even January.

Heated discharges may have application in irrigating and creating controlled environments for agricultural crops. In this manner, growing seasons could be lengthened in certain areas for common crops, and subtropical or tropical varieties might be produced where they are not normally adaptable.

Cooling water may provide heat to warm swimming areas. Such use should be guided by the National Technical Advisory Committee on Water Quality Criteria (76) which recommends: "In primary contact recreation waters, except where caused by natural conditions, maximum water temperature should not exceed 30°C (85°F)."

Thermal discharges may also provide heat for desalination or other processes, some of which might require higher temperature water than that normally discharged from steam plants. In such cases, it may be possible to implement a "trade-off" whereby it would be economical to alter the usual process for other benefits. For example, steam from the final turbine exhaust may be 80°F and 0.5 psia. If the steam were tapped off in front of the final turbine stage it may be 250°F and at 10 psig, which might be worth more for some use other than its final turbine passage. Marketable steam for use by other industries, for home heating, or for any other purpose may warrant "trade-off" situations which would help to reduce waste heat loads to streams and other water bodies.

Creation and application of improved technology for electrical energy conversion is an indirect, but effective, control measure. The advent of the fluorescent light is a classic example of getting more useful work from a watt of electricity. Other fertile areas are the heating, refrigeration, air-conditioning and motor industries.

COOLING DEVICES

Types

Waste heat rejection to the aquatic environment can be reduced through the use of cooling ponds or cooling towers. The most popular devices now in use in this country are various types of evaporative cooling towers. In the future, large reservoirs used as cooling ponds may find increased application in some areas.

Any method that provides air-water contact for cooling removes about 75% of the heat through evaporation and the remainder through conduction-convection. As water is vaporized, heat is consumed at the rate of about 1000 BTU per pound of water evaporated. Almost all of this heat is taken from the water that remains, thereby lowering its temperature.

Cooling Ponds

A cooling pond or reservoir is the simplest method of cooling thermal discharges, although it is the least efficient in terms of air-water contact. In a flow-through system, warm water is introduced at one end of the pond, cooled through heat dissipation to the atmosphere, and eventually withdrawn as cold water from the opposite end of the impoundment. Since the natural cooling process is relatively slow without induced air and water movement, surface area requirements may average about two acres per megawatt output, depending on local climatic conditions.

Advantages of cooling ponds or reservoirs include:

1. Low construction cost.
2. Serves as a large settling basin.
3. May be beneficial for other purposes, e.g., recreation.

Disadvantages are:

1. Low heat transfer rate, necessitating large land area.
2. Possible fogging, icing of nearby roads, etc.

Cooling can be accelerated in a pond by introducing the warm water through a spray system located 6 to 8 feet above the water surface. Such a system may reduce the required pond surface area by a factor of 20 through increased cooling efficiency. This advantageous savings in land area may be negated through spray system cost, pumping costs, and increased water loss with its associated problems.

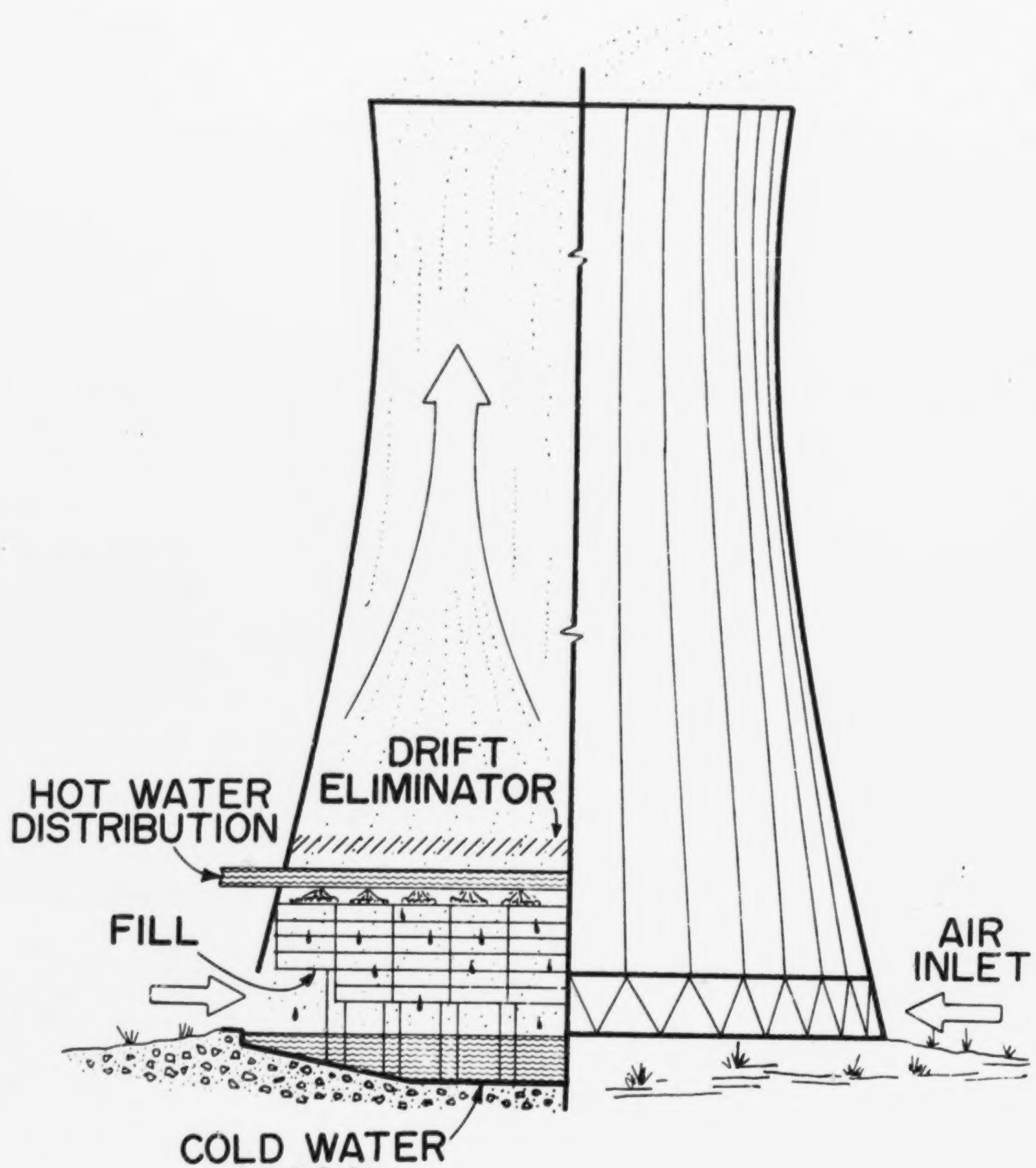
Cooling Towers

There are many versions of cooling towers. Terminology applied to towers stems from basic differences in design or operation which serve to categorize the types.

A tower may be either "wet" or "dry," depending on whether water is exposed directly to the air; "natural draft" or "mechanical draft," depending on whether fans are employed for air movement; "cross-flow" or "counter-flow," depending on horizontal or vertical air flow through the heat transfer section of the tower. In mechanical draft towers, air flow can be either "forced," i.e., pushed through by fan on bottom, or "induced," i.e., pulled through by fan on top. See Figures 3, 4, 5 and 6 for schematics (29,41) illustrating these types.

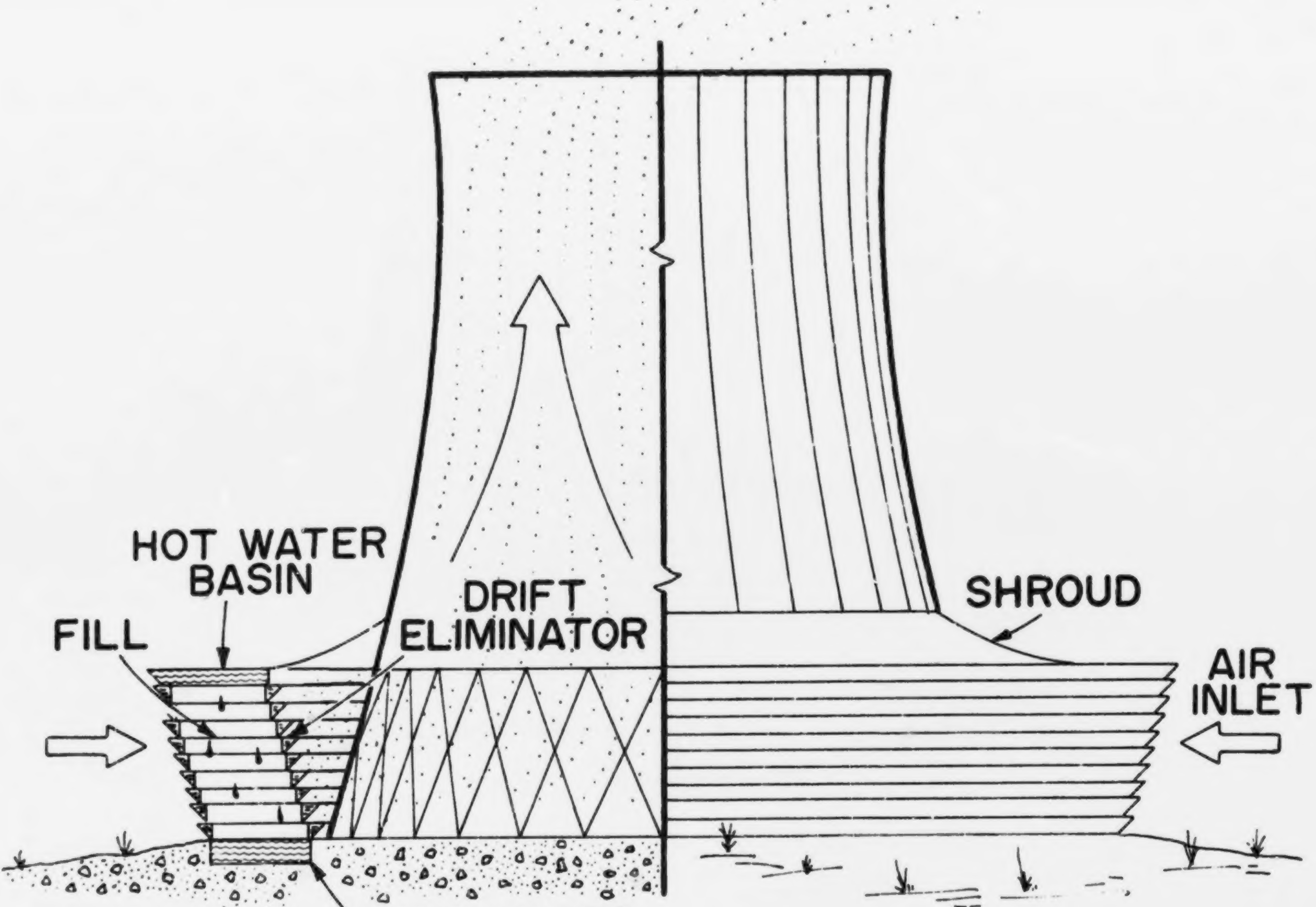
FIGURE 3

NATURAL DRAFT TOWER


DRIFT
ELIMINATOR
HOT WATER
DISTRIBUTION
FILL
AIR
INLET
COLD WATER
BASIN

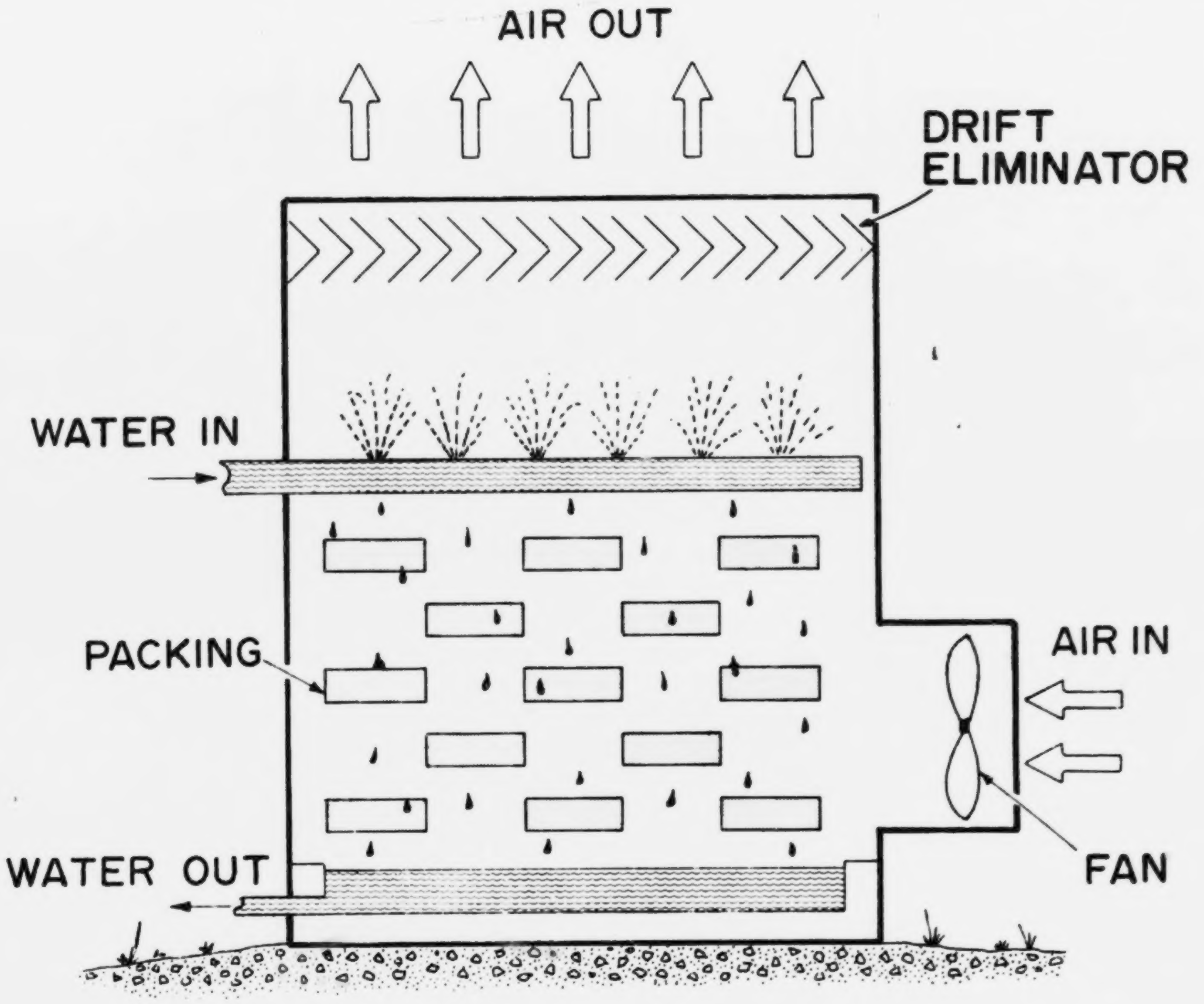
WET (Evaporative) COUNTERFLOW

FIGURE 4
NATURAL DRAFT TOWER


HOT WATER BASIN
FILL
DRIFT ELIMINATOR
SHROUD
AIR INLET
COLD WATER BASIN

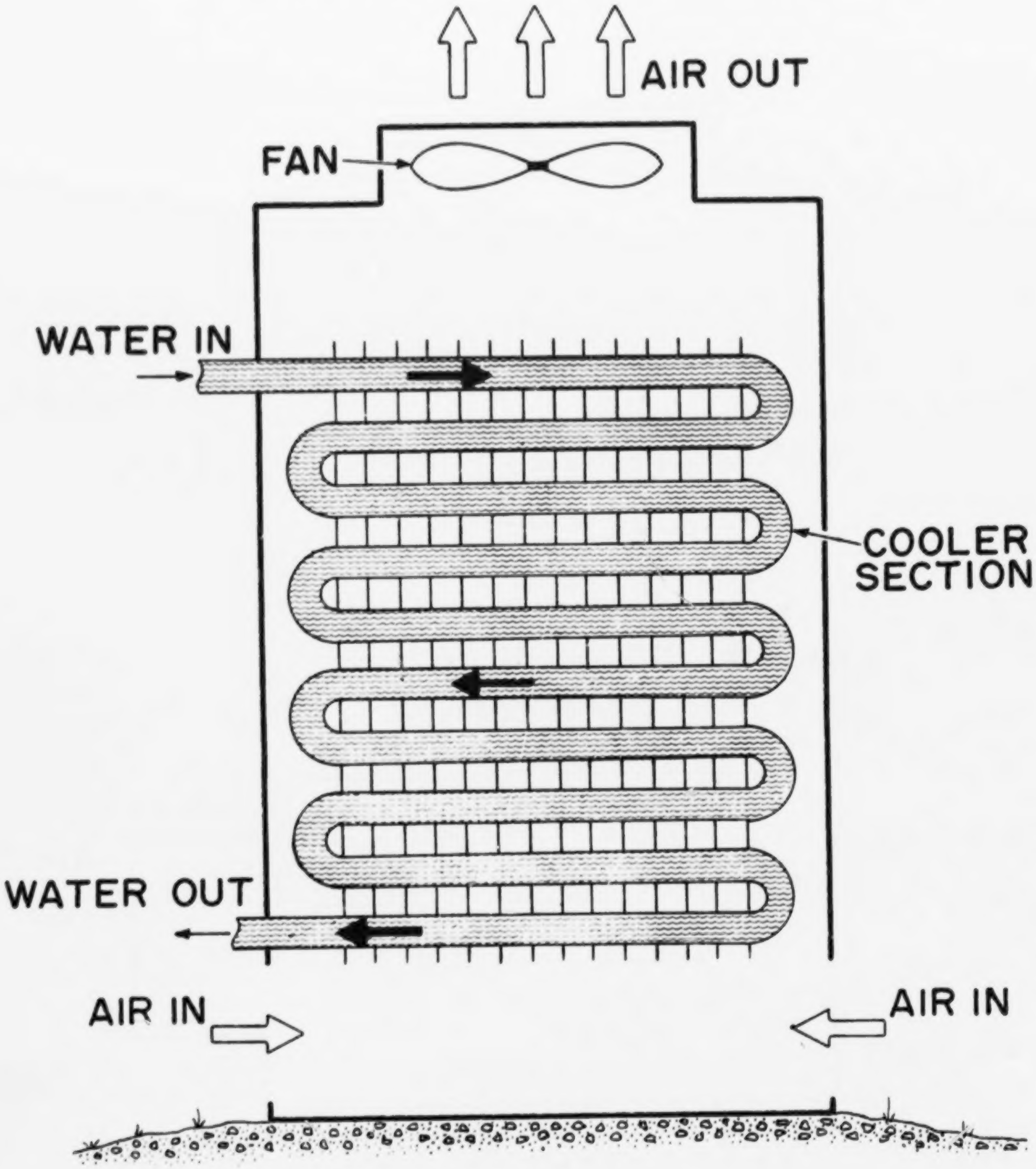
WET (Evaporative) CROSSFLOW

FIGURE 5
MECHANICAL DRAFT TOWER


AIR OUT
DRIFT ELIMINATOR
WATER IN
PACKING
AIR IN
WATER OUT
FAN

WET, (Evaporative) FORCED AIR FLOW

FIGURE 6
MECHANICAL DRAFT TOWER


AIR OUT
FAN
WATER IN
COOLER SECTION
WATER OUT
AIR IN
AIR IN

DRY, INDUCED AIR FLOW

Because it is important to understand the working language when discussing cooling towers, the following discussion of significant terms is presented.

Dry-Bulb Temperature: (^oF, ^oC) Temperature of air read on an ordinary thermometer.

Wet-Bulb Temperature: (^oF, ^oC) Obtained by covering the bulb of an ordinary thermometer with wetted gauze and reading in moving air. It depends on the dryness and initial temperature of the air, but is lower than dry-bulb temperature because some water evaporates from the gauze, removing heat. The wet-bulb temperature is the theoretical limit to which water can be cooled through evaporation.

Relative Humidity: (%) The ratio of the amount of water vapor actually present in the air to the greatest amount it could hold if saturated at that temperature and pressure. When relative humidity is 100%, wet-bulb temperature equals dry-bulb temperature; therefore, the lower the relative humidity, the greater the difference between wet-bulb and dry-bulb temperatures.

Evaporation Rate: The rate, e.g., gallons per minute, at which water is being evaporated to cool the circulating water. It depends on the area of air-water surface contact, length of time of contact, and difference between wet-bulb temperature of the air and water temperature.

Cooling Range: (°F, °C) The temperature difference between hot water entering a tower and cold water leaving.

Approach: (°F, °C) The temperature difference between cold water leaving a tower and wet-bulb temperature of the surrounding air.

Heat Load: (BTU/hr, BTU/min) The amount of heat dissipated in a cooling tower per unit time. It equals water circulation rate multiplied by cooling range, i.e.,

$$\left(\frac{\text{gal}}{\text{min}}\right) \quad \left(\frac{\text{lb}}{\text{gal}}\right) \quad \times \quad (^{\circ}\text{F}) \quad \left(\frac{\text{BTU}}{\text{lb}\ ^{\circ}\text{F}}\right) = \text{BTU/min}$$

Drift, Carry-Over, or Windage Loss: Water carried out of a tower in mist or small droplet form. It is usually expressed as a percentage of the circulating water rate. Caused by high air velocities, it can be almost entirely eliminated through good design and operation.

Basin: The depressed bottom portion of a tower used for collecting and storing cold water.

Blowdown: The continuous or intermittent discharge to waste of a small portion of circulating water from the tower basin. It is usually expressed as a percentage of the circulating water rate. It prevents build-up of dissolved solids left behind during evaporation.

Makeup: (gpm,cfs) Water required to replace normal system losses from evaporation, drift, blowdown, and small leaks.

Packing or Fill: Material placed in a tower over which water flows. It increases the air-water surface area and time of contact and maintains uniform air and water flow distribution. Packing design dictates the type of flow. Counter-flow towers usually use film-type packing; cross-flow towers usually use splash- or droplet-type packing.

Water Distribution System: A network of pipes (usually) which spreads incoming hot water uniformly over the packing in a tower.

Drift Eliminators: Baffles located above the water distribution system in a tower. As air flows through the baffles in a curved path, water particles are thrown from the airstream by centrifugal force.

Natural Draft Towers.--The cooling tower finding frequent application to large power plant discharges at the present time is the wet, natural draft, hyperbolic type. Over 20 of these towers are now in various stages of operation or construction in this country.

Hyperbolic towers derive their name from the hyperbolic profile of the reinforced concrete shell. The largest are almost 450 feet high and over 300 feet in diameter at the base. The function of the shell is that of a stack or chimney in providing an enclosure for air flowing through the packing which is located near the ground either inside or outside of the shell. Air flow through a tower is created by the difference in density between the internal and external air. Warm water passing through the packing heats the air and saturates it with water vapor during evaporative heat transfer. Both processes decrease the air density and cause it to rise up the tower. More air is drawn in, resulting in the establishment of a continuous air flow through the tower. External winds moving across the top of the tower also contribute somewhat to the air flow by reducing the internal pressure, thereby creating a drawing effect. However, tower operation is not dependent on external wind-induced air movement.

Internal packing is located in the bottom 10 to 20 feet of the tower shell. Warm water distributed above the packing flows downward through it in thin layers, contacting air rising vertically through the tower. Such opposed flow denotes the counter-flow classification. (See Figure 3)

Packing may also be located on the outside periphery of a shell. In this system the water is broken up into droplets by splash-type packing and allowed to fall downward. Incoming air flows horizontally through the falling water and then travels upward through the empty tower shell. This case describes the cross-flow classification. (See Figure 4) Water loading over the packing is from 2 to 4 gpm per square foot of horizontal area (29).

Advantages of the evaporative, natural draft type of tower are (48):

1. Does not have mechanical or electrical components, yet for a given load it has the same cooling capability as the mechanical draft type.
2. Low maintenance cost, both in time and money.
3. Independent of wind velocity.
4. Large water loading capacity.
5. For counter-flow design, air and water flows are opposite in direction, with the driest air meeting the colder water first, ensuring maximum efficiency.

Disadvantages are (48):

1. Internal resistance to air flow must be kept minimal.
2. Great shell heights are required to produce a draft.
3. Inlet hot water temperature must be hotter than air dry-bulb temperature to induce air movement.
4. Exact control of outlet water temperature is difficult to achieve.

Evaporative loss of water through the system amounts to about 1.5% of the flow circulated. Blowdown may require an additional 2 or 3%, depending on the quality of the circulating and makeup water. Drift is negligible in a well designed tower, not exceeding 0.2% of the circulating flow (41).

A fossil-fueled power plant in the 600 MW class or a nuclear-fueled plant of about 400 MW would discharge about 2500 X 10^6 BTU's per hour. Typical design conditions for a hyperbolic, evaporative tower to handle this heat load may be as follows (41):

Waterflow...........................	450 cfs
Hot Water Temperature...............	115°F
Cold Water Temperature..............	90°F
Design Wet-Bulb Temperature.........	72°F
Design Relative Humidity............	50%

Such conditions would require a tower about 400 feet high and 285 feet in diameter for counter-flow design, or about 370 feet high and 380 feet in diameter for cross-flow design (41).

Care must be exercised when comparing natural draft evaporative tower requirements at different sites. Each design is necessarily based on specific conditions--temperature, humidity, etc.--for a given geographical location. Hence, the size and performance cited for a tower at one plant site may not apply to another, even though the plants to be served are quite similar.

Other kinds of natural draft towers depend on air movement without the use of a chimney or shell.

Atmospheric spray-filled towers, which are really more like narrow spray ponds, have nozzles located from 6 to 15 feet high surrounded by a louvered fence which permits air passage but inhibits water loss. Air circulation is dependent mainly on wind velocity. Such cooling systems are suited for small refrigeration and engine-water jacket installations, where variations in a relatively small cooling range will not seriously hamper operations. Where locations permit prevailing winds to flow unobstructed, the system works fairly well with a minimum of maintenance. Water loading capacity may be up to 1.5 gpm per sq ft of active horizontal area with wind blowing at 5 mph (29). Disadvantages may include clogging nozzles, high pumping pressures required to atomize water, and high windage losses.

Atmospheric packed towers are similar to the spray-filled type except that they are usually larger and contain packing for water breakup and additional wetted surface exposure. Such systems are rarely built any more because of their high capital and pumping costs, and of their dependence on wind for air circulation. Small mechanical draft towers which handle comparable loads at similar costs are now preferred.

A final consideration in the natural draft category is the hyperbolic dry tower. This type also employs a shell for the draft effect, but utilizes indirect heat transfer instead of evaporation for cooling. Completely closed cooler sections give up heat through conduction-convection, hence there is no evaporative loss of heat or water. The indirect transfer of heat is much less efficient than the evaporative process so that much larger volumes of air must be circulated than in a wet tower. Therefore, the shell size must be larger, which adds to capital cost.

Dry towers are also at a disadvantage compared to wet types because of the lower limit to which water may be cooled. The theoretical lower limit in a dry process is the dry-bulb air temperature; the corresponding limit in a wet process is the wet-bulb temperature, which is usually appreciably lower (64).

Natural draft dry towers have not been generally used for large-scale cooling because the capital cost is estimated to be about three times as much as its wet counterpart (64). However, the elimination of water loss through the use of such systems may prove to be a deciding factor in their acceptance in some locations in the future.

Mechanical Draft Towers.--Until 1963 when the first hyperbolic, natural draft evaporative tower was built at the Big Sandy power plant at Louisa, Kentucky, only mechanical draft towers had been used in the United States.

Advantages of evaporative, mechanical draft cooling towers are (48):

1. Close control of cold water temperature.
2. Generally low pumping head.
3. Location is not critical.
4. More packing per unit volume of tower.
5. A smaller approach and greater cooling range are possible.
6. Small land area requirements.
7. Capital cost is less than for a natural draft chimney.

Disadvantages include the following (48):

1. High operating costs, including power.
2. High maintenance costs, both in time and money.
3. Subject to recirculation of hot, humid exhaust into the air intakes.
4. Climatic variation can affect performance because fans move a fixed volume of air regardless of its density and related heat transfer properties. Also, efficiency decreases as wind speed increases, up to a critical velocity; at velocities above the critical value the opposite is true because of less recirculation.

Mechanical draft towers are used over a broad range of heat loadings because they can be designed specifically for almost any capacity. Maximum fan sizes limit the capacity of any single cell, but additional cells may be built to form a bank or unit capable of meeting the total requirement.

The two air flow designs commonly used in mechanical draft towers, forced draft or induced draft, were referred to previously and depicted schematically in Figures 5 and 6.

Forced draft towers, with one or more fans located in the air intake, are slightly more efficient than induced draft types because some of the pressure of air velocity is converted to static pressure in the tower and recovered in the form of useful work. Fan location close to solid foundation lessens vibration. Also, locating fans at the air inlets reduces the possibility of moisture condensation on the equipment since most of the air moved is dry.

Recirculation of hot air is common in forced draft towers because of the proximity of the exhaust to the low-pressure air-intake region. Hence, efficiency may vary and winter operation often causes frost and ice formation on equipment or nearby buildings due to the presence of moisture-laden air near ground level.

Forced draft type fan diameters are limited to 12 feet or less, compared to nearly 60 feet for the induced draft type, which necessitates more cells for a given capacity (29).

While forced draft towers employ only counter-flow air movement through the packing, induced draft towers may use either counterflow or cross-flow design. The basic differences in packing design and arrangement, as described previously, apply here also. For either type of flow, recirculation is generally not a problem because the top-mounted fan discharges heated air upward, directly away from the air intake below. Because hot, humid exhaust air moves through the fan, corrosion of mechanical parts is more pronounced than in a forced draft system.

Operational pros and cons of cross-flow design versus counterflow design are fairly well balanced for operational characteristics. Physically, cross-flow types can be built lower and provide easier access to the water distribution system.

Mechanical draft systems also may provide air movement in dry towers, thereby fulfilling the purpose of the hyperbolic shell as previously discussed. As noted before, large volumes of air are required because of less efficient heat transfer through conduction and convection than through the wet evaporative process (64). Therefore, large fans are required which continuously demand an appreciable amount of power--about 3% of total electric power production (6). Economics related to mechanical draft dry systems discourage large-scale application at this time.

Side Effects

Concern over possible side effects from cooling devices has risen along with the projected use of such systems. Primary concern is with potential fogging conditions caused by cooling towers (14,62), but other possible adverse side effects should be considered.

Because of the large amount of water vapor expelled from evaporative towers, extreme climatic conditions may cause condensation, resulting in ground level fog or drizzle. However, such conditions are not often encountered in practice (48). A recent investigation of fogging problems from natural and mechanical draft towers presently operating in the eastern U.S. supports this conclusion (11). Reports indicate that natural draft towers did not produce ground-level fog or drizzle under any weather conditions. Plumes rarely dropped below the top of the tower for an extended distance, and generally dissipated within a few hundred feet of a tower. Mechanical, induced draft towers reportedly produced substantial amounts of ground level fog, especially during the winter. The area affected by the fog was very small, however, extending a maximum of about one-fourth mile from the towers. Carry-over of some water droplets was also noted from the mechanical draft type. Resulting precipitation occurred in the immediate vicinity of the towers, causing some minor icing problems up to 300 feet away.

In general, undesirable meteorologic effects from towers can be prevented or controlled to a large degree through modern design--effective drift eliminators, air-flow control, etc. In situations where problems arise, the area affected is limited to that immediate to the tower installation (16).

Water circulating through a condenser-cooling tower system may be treated chemically to prevent corrosion and inhibit biological growth (21). Hence, water extracted for blowdown purposes may contain constituents which would be detrimental to aquatic life in receiving waters. Such effects may be prevented by treating blowdown waste separately or, more efficiently, by integrating blowdown disposal with other plant waste disposal facilities.

Costs

An article (41) discussing natural draft, evaporative cooling towers states the following in regard to tower costs:

"Single towers, regardless of design, will cost in the area of $2.5 to $3.5 million each for the size of towers which have been utilized to date in the United States.

"The physical size and cost of a tower installation for a given size generating unit, however, can vary widely with location, fuel costs, load factors, and with individual practices regarding capability penalties and capitalization rates. It is possible that the optimum cooling tower installations for two plants with identical rated outputs could differ in cost by a factor of two. For this reason, it is difficult and, indeed, dangerous to generalize when discussing tower requirements and costs."

The following outlines cooling tower costs as related to each other, to total plant or production costs, and to consumer costs.

Natural draft evaporative tower capital costs in the eastern U.S. have been at least 5% of the total capital cost of a power plant. For a given plant heat load, mechanical draft, evaporative towers cost approximately two-thirds as much as natural draft; either natural draft or mechanical draft dry types would probably cost three to four times more than their wet counterparts.

The indicated savings in initial cost for the mechanical draft, wet tower is somewhat negated because of power costs for fans, which consume about 0.8% of the power generated by the unit served (44). For the proposed 540 MW nuclear plant at Vernon, Vermont, the annual cost for production of power to operate fans is estimated to be about $130,000--about 2% of the initial capital tower cost of $6 million. Other maintenance costs for the mechanical draft tower installation are estimated at $60,000 annually--1% of initial tower costs. For this plant, the initial cost for mechanical draft towers amounts to 5.1% of the total plant cost of $118 million (19).

In a detailed study for siting 1000 MW nuclear power plants in the Pacific Northwest (55), natural draft cooling towers were recommended at a number of locations. At all sites the estimated initial cost of such towers and related appurtenances was about $7.5 million, or approximately 5.5% of a total plant capital cost of about $140 million. Induced draft towers were recommended in one case, also at a capital cost of about 5.5% of the total plant cost. The cost of a 2600-acre pond at a location conducive to that type of cooling system would be about 2.3% of the total plant cost. It should be noted, however, that the pond location was in an area of relatively low land value.

These examples indicate that evaporative cooling systems will increase the capital cost of a power plant by about 5%. An assessment of all fixed and variable costs indicates that power production costs are also increased by about 5% (19). It should be noted, however, that such increases are not carried over to consumer costs in the same proportion because of intermediate fixed costs incurred through transmission and administration. According to Converse (19), production cost is only about one-fifth of consumer cost. In that case, the cost of electricity to the consumer, because of the use of evaporative cooling towers, would increase approximately 1%.

TRANSPORT AND BEHAVIOR MANIPULATION

Dispersion and Dilution Techniques

The design of discharge outfalls is, at the present time, more art than science. Hydraulic model studies, along with other empirical information, are now the basis for design because theoretical equations of fluid motion have not yet reached the stage of engineering application. Future developments in the area of mathematical models, hopefully, will place the design of outfall structures more on a theoretical, rather than empirical, basis.

The physical and hydraulic characteristics of the effluent and receiving water largely determine the rate of dispersion and areal extent of dilution. Rate of dispersion is a function of the existing turbulence of the receiving water, turbulence induced by the kinetic energy of the effluent, and the density gradient between the effluent and receiving water. The areal extent of dilution is a function of the dispersion rate plus the number and orientation of ports in the discharge manifold. Outfalls should be designed to accomplish specific objectives.

If the objective is to minimize temperature gradients within the water body, a diffuser designed to maximize induced turbulence and to distribute the discharge over a broad area is recommended. The diffuser pipe could be placed in any of the three spacial dimensions of the water body, but common practice is to use a horizontal diffuser pipe placed across the stream.

A discharge technique which is quite common with TVA is the use of a discharge channel which floats the warm water on the surface of the receiving stream or reservoir. The objective of this method is to maximize dissipation of heat to the atmosphere and minimize the water areas and volume affected by the effluent; mixing is not desired. By forming a warm water wedge over the cool receiving water, rapid heat loss to the atmosphere is encouraged by increasing the energy transfer due to evaporation, convection, and back radiation. Thus, the warm water wedge acts in much the same manner as a cooling pond. However, this technique results in sharp temperature gradients near the surface and serious problems can occur if temperature sensitive organisms are subjected to such gradients. For example, this technique would not be desirable on a stream inhabited by a cold-water fishery.

A third alternative discharge technique is to develop a thermal plume. A single-point discharge below the surface of the receiving water will result in a plume extending in the direction of the water flow and vertical density gradient. Mixing is promoted by both the energy of the receiving water's current and by the kinetic energy of the discharge. In some streams where plumes originate near the bed, vertical mixing is rather rapid, but lateral mixing is slower. For example, plumes from AEC's nuclear reactors at Hanford, Washington, on the Columbia River exhibit such characteristics.

A term which has recently been appearing in the literature regarding thermal pollution is "thermal block." A thermal block occurs when a warm water mass interferes with fish migration (76, p. 31). Outfalls should be designed to prevent such a block from occurring.

A final point must be made concerning the control of heated discharges by dispersion and dilution. Such techniques cannot be expected to solve the problems associated with the discharge of large heat loads into moderate volumes of receiving water. Any heated discharge which will promote excessive temperature rises will require the use of cooling devices.

Water Quality Management

Temperature Prediction

Mathematical and physical models of varying degrees of complexity have been developed to determine the fate and persistence of heat in quiescent waters, flowing streams, estuaries, and the ocean. The ability to predict water temperatures accurately is necessary in order to determine the thermal impact of:

1. Proposed waste heat discharges.
2. Changes in the hydraulic characteristics of a water body or stream--for example, due to the construction of a dam with its resulting flow regulation.
3. Releases of water from stratified reservoirs with multilevel outlets.
4. Unusual meteorological conditions.

The following discussion presents the basic approach which is used to solve temperature prediction problems. However, the mathematical formulation of the physical heat transfer processes which occur is not a simple matter. The scope of this guide prevents a presentation of the mathematical derivations leading to temperature prediction models for all situations. However, a simplified case is presented in the example problem of the next section. For information on more sophisticated models, the reader is urged to consult the technical literature. An excellent basic reference is the Edison Electric Institute's Publication No. 65-902, Heat Exchange in the Environment, by J. E. Edinger and J. C. Geyer, Department of Sanitary Engineering and Water Resources, The Johns Hopkins University, June 1, 1965 (27).

It is necessary to consider heat transfer mechanisms in water and between water and the atmosphere in order to describe temperature regimes mathematically. For localized problems, e.g., outfalls or plumes, the mechanisms acting in the water are most important; analysis of conditions throughout larger systems (rivers, reservoirs, etc.) requires emphasis on the air-water heat transfer mechanisms as well as those in water. In either case, specific predictions are desirable so that effective control or management techniques can be applied.

There are two heat transport mechanisms which occur in water--advection and dispersion or turbulent mixing. Advection is the transport of heat by the motion of a mass of water and is accomplished through ordinary streamflow, utilization of a discharge stream's kinetic energy, or water movement due to density gradients. Mathematical terms for advection express the rate of heat energy transfer in terms of the water mass temperature and velocity along longitudinal, lateral, and vertical axes.

Turbulent mixing or dispersion cause heat interchange through eddy diffusion or molecular diffusion. Eddy diffusion occurs under turbulent flow, which depends on fluid velocity and channel characteristics. Mixing results from the action of small fluid masses known as eddies, which are random both in size and orientation. Molecular diffusion is that resulting from random motion of molecules. Its influence is much less than that from turbulent mixing. Diffusion effects are combined in mathematical expressions, and may be defined along longitudinal, lateral, and vertical axes.

Heat exchange which takes place between the water surface and the atmosphere is made up of seven mechanisms.

The mechanisms which are independent of water temperature are (27):

Q_s = Incoming short-wave solar radiation (400 to 2800 BTU/ft^2/day).

Q_a = Incoming long-wave atmospheric radiation (2400 to 3200 BTU/ft^2/day).

Q_{sr}, Q_{ar} = Portions of both short-wave and long-wave radiation which are reflected or scattered by the water surface (40 to 200 and 70 to 120 BTU/ft^2/day, respectively).

The mechanisms of heat transfer which are dependent on the surface water temperature include the following (27):

Q_{br} = Long-wave back radiation from the water to the atmosphere (2400 to 3600 BTU/ft^2/day). It is proportional to the fourth power of the absolute water surface temperature (AT_s), i.e., $Q_{br} \propto (AT_s)^4$.

Q_c = Heat exchange due to conduction-convection (-300 to +400 BTU/ft^2/day), which is proportional to the wind speed (W) and the difference between water temperature

(T_s) and air temperature (T_a), i.e., $Q_c \propto W(T_s - T_a)$. A positive Q_c indicates an energy loss.

Q_e = Heat loss due to evaporation (2000 to 8000 BTU/ft^2/day), which is proportional to the product of wind speed (W) and the difference between the water vapor pressure in saturated air at the water temperature (e_s) and the water vapor pressure in the overlying air (e_a), i.e., $Q_e \propto W(e_s - e_a)$. If $e_a > e_s$, condensation takes place and the water body gains energy.

The algebraic sum of these surface heat exchange parameters is equal to the net rate of surface heat exchange. Equilibrium temperature is reached when this sum is zero.

Micro Models.--In temperature prediction terminology, a micro model is one which describes or predicts the distribution of heat in the immediate vicinity of a thermal discharge. The micro models available at the present time are based on many simplifying assumptions which render them less than totally adequate for predicting local temperature distributions. However, they are useful for approximating heated discharge dilution rates by receiving waters. Theoretical work is progressing in areas such as mixing and dispersion and will aid in development of generalized micro models for jets and plumes.

Another factor which adds to difficulties with micro models is the unique character of many situations. For example, the nature of a stream channel at any location will influence mixing characteristics. Curvature or depth variation may direct discharges into certain portions of a channel, thereby nullifying the theoretical description of the length or degree of mixing. Each situation will therefore require careful description in terms of discharge pumping rate, river flow, and channel characteristics.

Until generalized micro models can accurately predict local temperature distributions under various hydraulic conditions, estimates based on simplified models and past experience will be required.

Macro Models.--Macro models are those which describe or predict temperature regimes in a complete river or river system, lake or reservoir, estuary, or coastal area. Such models combine heat transfer mechanisms and water movement on a continual basis with respect to time. With the current state of the art, technology for macro-prediction is more reliable than for micro-prediction. This is possible because of the compensating and averaging effects of spacial differences in environmental variables.

A macro model maintains an energy budget for the water body under consideration, i.e., it maintains a heat balance of both the internal heat exchange and the heat transfer at the water surface. This heat budget may be expressed as follows:

(Rate of Heat In) - (Rate of Heat Out) + (Rate of Heat Storage) + (Rate of Heat Exchange at Water Surface) = 0

The rate at which heat flows into and out of the water body is determined from the flow rates and temperatures of inflowing and outflowing water. These rates require evaluation of the heat transfer mechanisms in water to define the motion of heat entrained water masses. The rate of heat storage is determined from the temperature and volume of the water body in consecutive time periods. The rate of heat exchange at the water surface is the algebraic sum of all the water-atmosphere heat exchange rates.

Macro models evaluate terms in the heat budget over specific time periods, e.g., hourly, daily, weekly, etc. The rate-time evaluation results in quantitative values for each portion of the heat budget for each period through the study time span. By superimposing flow rates on the time scale, the location of a specific water mass may be determined at any desired time. For temperature prediction, a model routes hypothetical masses of water along a described course in order to simulate their movement and changes in thermal properties; temperatures are thereby predicted at specific locations and points in time.

Thermal Regulation

The need to manage our environment has only recently been recognized, but we now realize that in order to continue tne effective use of our natural resources, environmental management is a necessity. In terms of thermal pollution control, we can perform water temperature management through plant siting, coupled with effective use of regulated river systems. Effective water temperature prediction models will enable water resources managers to predict temperatures which will result from combined dam releases and thermal inputs to a system. Conditions can then be selected to minimize undesirable thermal effects. Such temperature-discharge requirements can be met through the use of multilevel dam outlets which permit waters of various temperatures to be selectively released from stratified reservoirs.

EXAMPLE PROBLEM

This section presents a problem concerning temperature prediction on a well-mixed stream and the sizing of flow-through cooling ponds. A complete explanation of the methodology is beyond the scope of this guide, and the reader is urged to consult the literature for an in-depth review of the many available computational techniques. The problem solution uses basic methods, all of which can be found in the publication by Edinger and Geyer (27). As an aid in analyzing the problem, references to appropriate pages in this reference are given.

The Situation

A 1000 MW electrical output nuclear power plant of 33% efficiency is to be located on a medium-sized river in the temperate region of the nation. Using applicable hydrologic and meteorologic data, we wish to compute:

A. Downstream temperature, assuming once-through cooling and complete mixing in the river.

B. The area of a flow-through cooling pond necessary to prevent violation of water temperature standards.

Part A

Compute the heat energy entering the cooling water as described in the "Plant Evaluation" section.

1. For 33% thermal efficiency (η_t):

   $$\text{Heat Rate} = \frac{3413}{\eta_t \div 100} = \frac{3413}{.33} = 10{,}340 \text{ BTU/KWH}$$

2. Assuming a 5% in-plant heat loss:

   Heat to cooling water = (0.95 x Heat Rate - 3413) BTU/KWH

   Heat to cooling water = [0.95(10,340) - 3413] BTU/KWH

   Heat to cooling water = 6410 BTU/KWH

   Total heat to cooling water for the 1000 MW (10^6 KW) plant =

   10^6 KW x 6410 BTU/KWH = $\underline{\underline{6.41 \times 10^9 \text{ BTU/hr}}}$

Compute the temperature rise in the stream, assuming once through cooling and complete mixing.

Given a design flow in the stream of 3500 cfs, which in terms of lb/hr is:

$$Q = (3500 \text{ cfs})\ (62.4 \text{ lb/ft}^3)\ \ (3600 \text{ sec/hr})$$

$$Q = 7.86 \times 10^8 \text{ lb/hr}$$

Since 1 BTU will raise the temperature of 1 lb of water 1°F,

$$\Delta T_r = \Delta T \text{ in river} = \frac{(6.41 \times 10^9 \text{ BTU/hr})}{(7.86 \times 10^8 \text{ lb/hr})\ (1 \text{ BTU/lb }^{\circ}\text{F})}$$

$$\Delta T_r = \underline{\underline{8.2^{\circ}\text{F}}}$$

Equation for computing downstream temperatures.

Downstream temperatures are computed by assuming exponential temperature decay. This concept is presented mathematically as:

$$\frac{dH}{dt} = -K(T - E) \qquad (27, \text{ p. } 43)$$

where $\frac{dH}{dt}$ = net rate of water surface heat exchange (BTU ft^{-2} day^{-1})

K = energy exchange coefficient (BTU ft^{-2} day^{-1} $^{o}F^{-1}$)

T = water surface temperature (^{o}F)

E = equilibrium temperature (^{o}F)

For a well-mixed stream, this equation can be written as:

$$\rho C_p y U \frac{\partial T}{\partial x} = -K(T_x - E) \qquad (27, \text{ p. } 129)$$

where ρ = water density (62.4 lb ft^{-3})

C_p = specific heat of water (1 BTU lb^{-1} $^{o}F^{-1}$)

y = mean stream depth (ft)

U = mean stream velocity (ft day^{-1})

$\frac{\partial T}{\partial x}$ = longitudinal temperature gradient (^{o}F ft^{-1})

x = downstream distance (ft)

Define T_o = temperature at $x = o$; then

$$T_x = (T_o - E)e^{\left(\frac{-Kx}{\rho C_p y U}\right)} + E$$

By defining $\alpha = \frac{-Kx}{\rho C_p y U}$; then

$$\underline{\underline{T_x = (T_o - E)e^{\alpha} + E}}$$

Meteorologic Data

The following data are used in determining K and E:

	For K	For E			
Time Period (6 hr intervals)	Wind Speed (W) (mph)	Net Radiation Input (H_R) (BTU ft^{-2} hr^{-1})	Air Temp (T_a) (°F)	Relative Humidity (%)	Water Vapor Pressure of Ambient Air (e_a) (mm Hg)
Midnight - 6 am	4.0	120	65	40	6.3
6 am - Noon	12.0	290	75	30	6.7
Noon - 6 pm	12.0	320	85	20	6.2
6 pm - Midnight	6.0	130	70	35	6.6
DAILY AVERAGE	8.5	215	74	--	6.5

Determination of K

The energy exchange coefficient is computed using a variation of the equation given on page 48 (27):

$$K = [15.7 + (0.26 + \beta)(bW)]$$

where W = wind speed (mph)

b = experimental evaporation coefficient (a value of 15 is used in this example)

β = proportionality coefficient [See following table]

Range of E (°F)	β (mm Hg $°F^{-1}$)
50 to 60	0.405
60 to 70	0.555
70 to 80	0.744
80 to 90	0.990

Thus, for an average daily value of K, using W = 8.5 mph:

$$K = (15.7 + [0.26 + \beta] [(15) (8.5)])$$

Using appropriate values of β for two ranges of E:

E (^{o}F)	K(BTU ft^{-2} day^{-1} $^{o}F^{-1}$)
60 to 70	120
70 to 80	144

Determination of E

The equilibrium temperature is reached when the rate of change of energy at the water surface equals zero. Edinger and Geyer (27) present a method for computing E (pp. 55-59). The method involves assuming a likely 10^{o}F temperature range for E and by using the appropriate value for K and the given meteorological data, computing a value for E. If the computed value of E falls within the assumed range, the process is complete. However, if the computed value of E falls outside the assumed range, another range must be assumed and the process repeated until E falls within the proper limits. Thus, E is computed by a trial and error method.

For the stated meteorological conditions and computed values of K, we can determine a daily average E by the following seven steps (27):

Step 1. Assumed range of E = 70 to 80^{o}F

Step 2. Compute F(K) for use in step 6:

$$F(K) = \frac{K - 15.7}{K}$$

As computed for an E range of 70 to 80°F, K = 144 BTU ft^{-2} day^{-1} $^{o}F^{-1}$

$$\therefore F(K) = \frac{144 - 15.7}{144} = 0.891$$

Step 3. Compute E_1 for use in step 6:

$$E_1 = \frac{H_R - 1801}{K}$$

From the meteorologic data table, H_R = 215 BTU ft^{-2} hr^{-1}

or in terms of days, H_R = 5160 BTU ft^{-2} day^{-1}

$$\therefore E_1 = \frac{5160 - 1801}{144} = 23.3$$

Step 4. Compute E_2 for use in step 6:

$$E_2 = \frac{(0.26)\ (T_a)}{(0.26 + \beta)}$$

From the meteorologic data table, T_a = 74°F, and from the table of E range vs. β, $\beta = 0.744$

$$\therefore E_2 = \frac{(0.26)\ (74)}{(0.26 + 0.744)} = 19.2$$

Step 5. Compute E_3 for use in step 6:

$$E_3 = \frac{e_a - C(\beta)}{(0.26 + \beta)}$$

From the meteorologic data table, e_a = 6.5 mm Hg. $C(\beta)$ is related to ranges of E as follows:

Range of E (°F)	$C(\beta)$ (mm Hg)
50 to 60	-11.22
60 to 70	-20.15
70 to 80	-33.30
80 to 90	-53.33

Thus for an E range of 70 to $80^{o}F$, $C(\beta) = -33.3$

$$\therefore E_3 = \frac{6.5 - (-33.3)}{(0.26 + 0.744)} = 39.6$$

Step 6. Compute M for use in step 7:

$$M = E_1 + F(K)\ (E_2 + E_3)$$

$$M = 23.3 + (0.891)\ (19.2 + 39.6) = 75.7$$

Step 7. Compute E using the following relationship:

$$M = E + \frac{0.051E^2}{K}$$

Inserting M and K and setting up a quadratic equation gives:

$$E^2 \left(\frac{0.051}{144}\right) + E - 75.7 = 0$$

$$\therefore 0.000354E^2 + E - 75.7 = 0$$

Solving this equation using the quadratic formula gives:

$$E = \frac{-1 \pm [1 - (4)\ (0.000354)\ (-75.7)]^{1/2}}{2\ (0.000354)}$$

$$E = \frac{-1 \pm (1.10719)^{1/2}}{0.000708} = \frac{-1 \pm (1.05223)}{0.000708}$$

Rejecting the negative value gives:

$$E = \frac{0.05223}{0.000708} = \underline{\underline{73.8^{o}F}}$$ (This value is acceptable because it falls within the assumed range of 70 to 80°F.)

Compute Average Stream Velocity

$Q = 3500$ cfs

Given an average cross section 800 feet wide and 5 feet deep:

$$U = \frac{3500\ ft^3\ sec^{-1}}{(800\ ft)\ (5\ ft)} = 0.875\ ft/sec = \underline{\underline{75{,}600\ ft/day}}$$

Evaluation of α

$$\alpha = \frac{-Kx}{\rho C_p y U}$$

For x' in miles: $\alpha = \frac{-(144)\ (5280)x'}{(62.4)(1)(5)(75{,}600)}$

$$\alpha = \underline{\underline{-0.0322x'}}$$

Solve for $T_{x'}$ for x' = 10, 20,....50 miles

Assume unheated river temperature = 74°F

$\therefore\ T_o = 74^oF + \Delta T_R = 74^oF + 8.2^oF = 82.2^oF$

$T_{x'} = (T_o - E)e^{-0.0322x'} + E$

For x' = 10 miles

$T_{x'} = (82.2 - 73.8)e^{-(0.0322)(10)} + 73.8$

$T_{x'} = (8.4)e^{-0.322} + 73.8$

$T_{x'} = (8.4)\ (0.725) + 73.8 = \underline{\underline{79.9}}^oF$

For x' = 20 miles

Use same value of α and replace T_o by $T_{x'}$ for x' = 10 miles:

$T_{x'} = (79.9 - 73.8)\ (0.725) + 73.8 = \underline{\underline{78.2^oF}}$

For x' = 30, 40, 50 miles

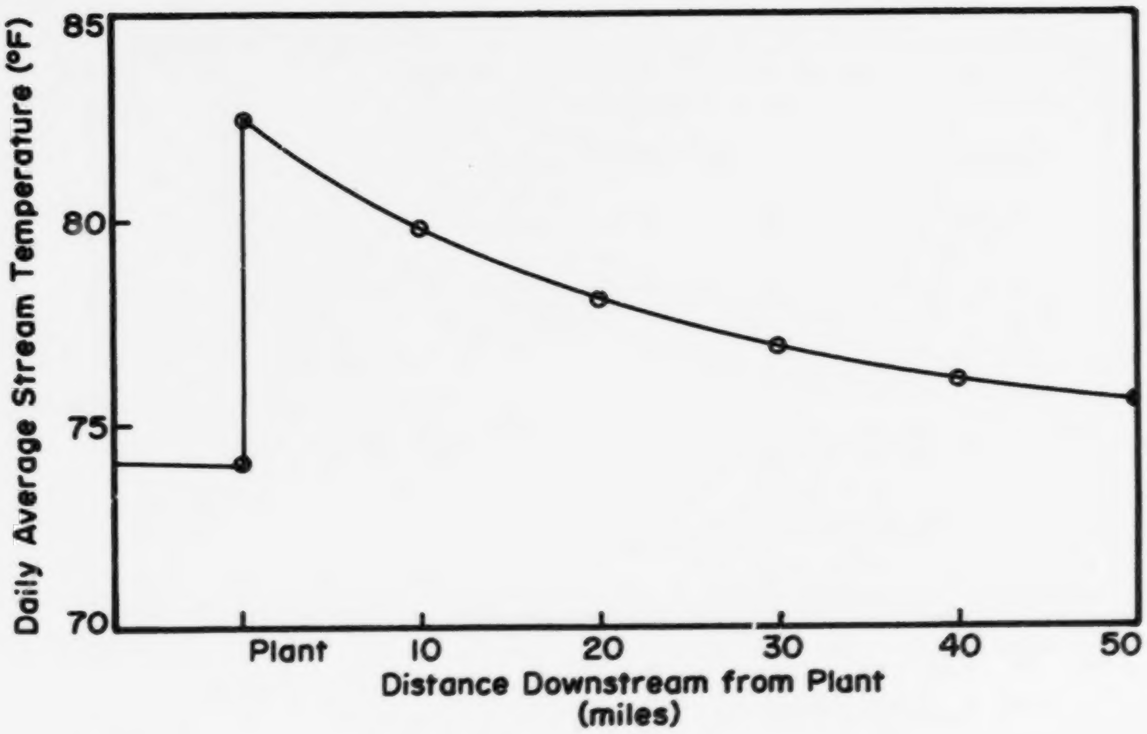
Following the same procedure:

30 miles, $T_{x'} = (78.2 - 73.8)\ (0.725) + 73.8 = 77.0^oF$

40 miles, $T_{x'} = 76.1^oF$

50 miles, $T_{x'} = 75.5^oF$

These values represent the exponential temperature decay which is graphically shown on the following plot:



This graph presents an idealized picture of the downstream temperatures, since the computations were based on average daily conditions, and thus no diurnal effect is evident. It also assumes that the weather data on which K and E are based are indicative of conditions along the 50-mile stretch of the river. In addition, no tributary inflows or heated discharges are accounted for in the 50 miles.

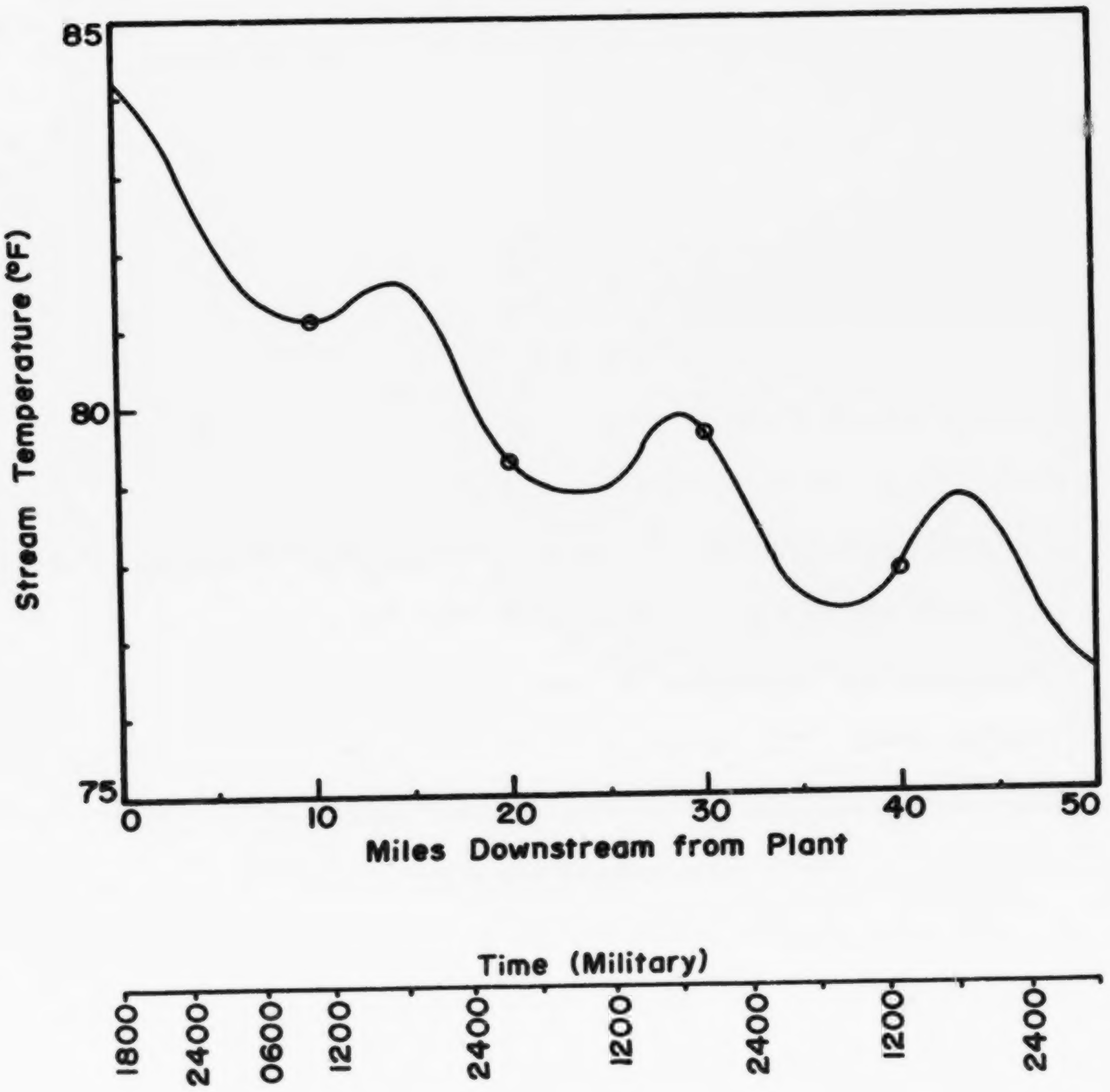
The diurnal effect may be evaluated by using the six-hour average meteorologic conditions given previously. Following the methods described, values of K and E were computed as:

Time Period (6 hr intervals)	K (BTU ft^{-2} day^{-1})	E (^oF)	T_o (^oF)
Midnight to 6 am	56	53.8	71
6 am to Noon	196	79.2	72
Noon to 6 pm	241	84.0	78
6 pm to Midnight	76	58.1	76

The values of water temperature (T_o) just upstream from the plant reflect natural diurnal fluctuations.

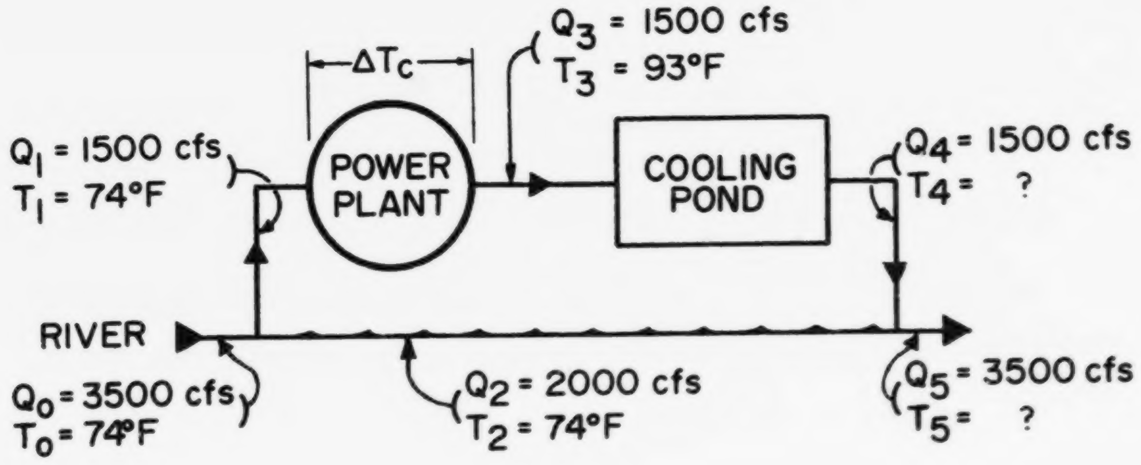
Using the exponential temperature decay relationship presented previously and assuming slug flow in the stream, i.e., no longitudinal mixing, the variation in temperature was computed for a parcel of water which left the plant location at 6 pm. The following graph demonstrates the effect of diurnal variations in meteorological conditions on the temperature of the water parcel for a distance of 50 miles downstream. Note that the initial temperature of the parcel is equal to the natural stream temperature (T_o) plus the temperature increase of 8.2^{o}F caused by the plant discharge.

TEMPERATURE OF A WATER PARCEL



Part B

Assuming a maximum allowable daily average stream temperature of 80^{0}F, what flow-through cooling pond area would be required at the site? The following sketch describes the plant-river-pond layout:


ΔT_c
Q_3 = 1500 cfs
T_3 = 93°F
Q_1 = 1500 cfs
T_1 = 74°F
POWER PLANT
COOLING POND
Q_4 = 1500 cfs
T_4 = ?
RIVER
Q_0 = 3500 cfs
T_0 = 74°F
Q_2 = 2000 cfs
T_2 = 74°F
Q_5 = 3500 cfs
T_5 = ?

Temperature Rise Through Plant

Heat to cooling water = 6.41×10^9 BTU/hr

Condenser flow = 1500 cfs = 3.37×10^8 lb/hr

$$\Delta T_c = \Delta T \text{ through condenser} = \frac{(6.41 \times 10^9 \text{ BTU/hr})}{(3.37 \times 10^8 \text{ lb/hr})(1 \text{ BTU/lb } ^{\circ}\text{F})} = 19.0^{\circ}\text{F}$$

$$\therefore T_3 = 74^{\circ}\text{F} + 19^{\circ}\text{F} = \underline{\underline{93^{\circ}\text{F}}}$$

Temperature Drop Through Pond

A flow-through cooling pond is assumed to be well mixed in each cross section, but as in a stream, there is a longitudinal temperature decay. Thus, the equation for predicting the temperature drop through the pond is equivalent to the exponential temperature decay equation used on well-mixed streams.

Using the temperature subscripts given on the sketch, the temperature from the pond can be computed by:

$$\underline{\underline{T_4 = (T_3 - E)e^{-\alpha'} + E}} \qquad (27, \text{p.}113)$$

where $\alpha' = \frac{KA}{\rho C_p Q_3}$

Q_3 = plant discharge ($\text{ft}^3 \text{ day}^{-1}$)

A = pond area (ft^2)

Using an experimental evaporation coefficient (b) of 12, K = 118 and E = 76.9°F. These values are used in the subsequent cooling pond calculations.

Case I - Pond area required for discharge from pond = 80°F.

$\therefore\ T_4 = 80^{\circ}F$

Solving the prediction equation for α':

$80 = (93 - 76.9)e^{-\alpha'} + 76.9$

$e^{-\alpha'} = (80 - 76.9) / (93 - 76.9)$

$e^{-\alpha'} = 0.193$

$\therefore\ \alpha' = 1.65$

Solving the α' equation for A:

$$\alpha' = \frac{118A}{(62.4)\ (1)\ (1500)\ (24\ \text{hr/day})\ (3600\ \text{sec/hr})}$$

$\alpha' = (1.46 \times 10^{-8})A = 1.65$

$\therefore A = (1.65)/(1.46 \times 10^{-8}) = 11.3 \times 10^{7}\ \text{ft}^2$

In acres: $A = \dfrac{(11.3 \times 10^{7}\ \text{ft}^2)}{(4.36 \times 10^{4}\ \text{ft}^2/\text{acre})} = \underline{\underline{2590\ \text{acres}}}$

Case II - Pond area required for mixed river temperature = 80°F.

If a mixing zone is allowed in the stream such that the mixed river temperature below this zone is equal to or less than 80°F, a much smaller pond could be used.

Referring to the sketch:

$$T_5 = \frac{T_4Q_4 + T_2Q_2}{Q_5} = 80^oF$$

Solving for T_4:

$$T_4 = \frac{T_5Q_5 - T_2Q_2}{Q_4} = \frac{(80)\ (3500) - (74)\ (2000)}{1500}$$

$$\therefore T_4 = 88.0^oF$$

By using the same computational techniques as for Case I:

$\alpha' = 0.373$

$\therefore\ A = (0.373)/(1.46 \times 10^{-8}) = 2.55 \times 10^7\ ft^2$

In acres: $A = \frac{(2.55 \times 10^7\ ft^2)}{(4.36 \times 10^4\ ft^2/acre)} = \underline{\underline{585\ acres}}$

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